GEOCHEMISTRY AND GEOLOGY

MINERALIZED AND BARREN KOMATIITES - WESTERN AUSTRALIA

BY

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A thesis submitted to the Department of Geology in fulfilment of the requirements for the degree of Master of Science.

University of Tasmania
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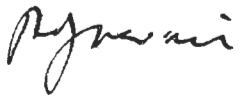

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ABSTRACT OR SUMMARY ?

Western Australian Archaean komatiites which are associated with nickel sulphide mineralization can be separated into two groups - Mineralized or Barren, based on komatiite lithogeochemistry. Mineralized komatiites may host nickel sulphide deposits whereas Barren komatiites do not. Chemical relationships were determined from a data base of approximately 3300 samples of fresh komatiite ultramafic from four nickel provinces and other greenstone belts not known to contain nickel sulphides. Mean chemical values for each group of komatiites were:

Category	NiP (1) (2)	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co
Mineralized	1027	2220	36	42	1.6	2.2	19.2	69	1617	1057	6.1	49	119
Barren	429	1530	29	39	2.2	2.8	16.4	76	2260	1128	7.0	32	119

Discriminant analysis, using the above thirteen chemical determinations as variables, for each of 2775 samples from forty localities, indicated that samples could be classified as either Mineralized or Barren with an expected accuracy of greater than 80 percent. No single element or chemical determination is definitive, but collectively, Cr, Ni, Zn, Cu, NiP, Mg, Fe and Co can distinguish between the two groups of ultramafics. Critical elements are Cr, Ni and NiP, assuming that values of Zn, Cu, Mg and Fe approximate the mean value for all West Australian komatiites. The Ni to Cr ratio is always greater than unity (1) in Mineralized komatiites and the Ni to NiP ratio is always less than 3.5. Sulphur is not a diagnostic element.

NOTES:

1. P indicates a partial or sulphide analysis.
2. Al, Ca, Mg and Fe results are expressed in percentages; all others in parts per million.

Increasing Ni/Cr ratios and decreasing Ni/NiP ratios within a komatiite can be regarded as indicative of increasing nickel sulphide potential. Mineralized komatiites contain less Cr within the silicate lattice structure and less chromite than Barren komatiites. However, the more important relationship appears to be the lesser amount of Cr attached to the silicate mineral lattice.

Correlation analysis showed that:

1. most correlations are much stronger in Barren than in Mineralized ultramafics;
2. the chalcophile elements, Cu, Ni, Co and Fe (constituents of nickel sulphide deposits), show moderate to strong correlations with the rock forming elements, Mg, Mn, Ca, Al in Barren ultramafics, but only weak or no correlation in the Mineralized ultramafics;
3. copper has moderate positive correlation with Fe, Mn, Ca, Al and negative correlation with Mg in Barren ultramafics but shows no correlation with these same elements in Mineralized ultramafics.

These correlation differences suggest that in Barren komatiites Ni, Cu, Co and Fe are contained in the silicate mineral lattice whereas in Mineralized komatiites they are presently partly as a separate sulphide fraction. In addition they may also suggest that these sulphides were added or removed from Mineralized komatiites after the formation of the komatiite magma, probably by concentration and removal in an immissible sulphide-oxide melt.

Komatiites can be divided into two separate suites called volcanic and intrusive. Volcanic suites such as those at Kambalda and Windarra South may contain many individual komatiite flows. The basal section of a komatiite volcanic pile consists of a small number of thick units which may contain sulphide mineralization whereas the central and upper parts of the pile consists of multiple thin units. Both thick and thin units consist of an olivine cumulate derived lower part overlain by a silicate liquid derived upper part. In thick units the olivine cumulate section is dominant whereas in thin units the

silicate liquid section is dominant. Spinifex texture is characteristic of unmetamorphosed sequences.

In metamorphosed sequences such as Windarra South it is not possible to identify individual komatiites using mineralogical or textural criteria but it can be accomplished using chemical data.

Intrusive suite komatiite sequences such as Forrestania or Perseverance usually consist of a small number of high Mg, homogeneous peridotites and/or dunites. Equigranular, equant olivine textures are characteristic. These komatiites are often continuous over strike lengths of the order of tens of kilometers and contain relatively little internal chemical variation.

Volcanic komatiites such as those at Windarra South and Kambalda are considered to be ultramafic lavas. Chemical differences between volcanic and intrusive sequences have been defined. Typical chemical values for the cumulate section of a volcanic komatiite and for intrusive komatiites, both with moderate to high mineralization coefficients are:

Classification	NiP	Ni	CuP & Cu	Al	Mg	Zn	Cr	Mn	Fe	CoP	Co
Volcanic Komatiites	1000	2100	30 - 90	1-2	17-24	60	1300	1000	5.5	55	120
Intrusive Komatiites	1200	2500	5 - 60	0.5	20-26	60	1000	900	6	60	125

In general, if NiP or Ni are less than 500 and 1800 ppm respectively, or Cr greater than 2100 ppm, a komatiite can be regarded as Barren.

It has been possible to define sections of greenstone belts as prospective for nickel sulfides and other parts as unprospective. For example, the Forrestania section of the Forrestania-Southern Cross greenstone belt has a different chemical signature to the Southern Cross section. The latter section is unlikely to contain economic nickel sulphide accumulations.

ACKNOWLEDGEMENTS

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Most of the geologic maps used for location purposes or for geological descriptions of specific areas are based on field mapping by other geologists. The names of many of these geologists are unknown but M. Lennox, J. Noakes and M. Woodhouse, all formerly of Tenneco Australia Inc. deserve specific acknowledgement. However, all solid geology interpretive maps and sections presented here are the responsibility of and have been compiled by the writer.

The writer especially wishes to thank the above three geologists for their assistance and for many stimulating discussions. Thanks are also due to E.A. Rugg formerly of Tenneco Australia Inc. and E.H. Lindsey of Union Oil Co. of California for their support throughout much of the study.

W.R. Guthrie, also formerly of Tenneco Australia Inc., was responsible for most of the analytical procedures and results. The description of analytical procedures are based on personal communications and notes from Guthrie.

P. Walker and N. Campbell deserve thanks for explaining the statistical procedures to the writer. The description of Mulvar in Appendix E is based on unpublished notes by J. Keays.

Finally I express my sincere thanks to Pamela Strauss for the final typing of this manuscript.

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CHAPTER I

1. INTRODUCTION

Define komatiite

Nickel sulphide deposits in Western Australia are generally related to komatiite (Naldrett and Cabri 1976) intrusive and volcanic rocks. They occur as disseminated and massive sulphide accumulations at or near the basal interface of komatiites with other rocks; less commonly at internal komatiite contacts; or as widespread, low grade disseminations within komatiite intrusives. However, only a small percentage of the many thousands of strike miles of komatiite ultramafic within the Yilgarn Block (Trendall 1975) of the Western Australian Archaean Shield (Fig. 1) contain, or are prospective for nickel sulphides.

A lithogeochemical study of komatiites was undertaken with the following objectives:

1. to determine if komatiites could be classified as Mineralized or Barren, based on certain major and minor chemical components;
2. to define the chemical characteristics of the volcanic and intrusive komatiite suites;
3. to provide data on the internal structure and compositional variations within komatiite sequences;
4. to provide a better understanding of the genesis of komatiites.
5. to compare the lithogeochemistry of komatiites from widely scattered nickel provinces and greenstone belts, to determine if significant chemical differences existed on a geographic basis;
6. to determine if chemical gradients within komatiite sequences could be recognized along and/or across strike from nickel sulphide accumulation.

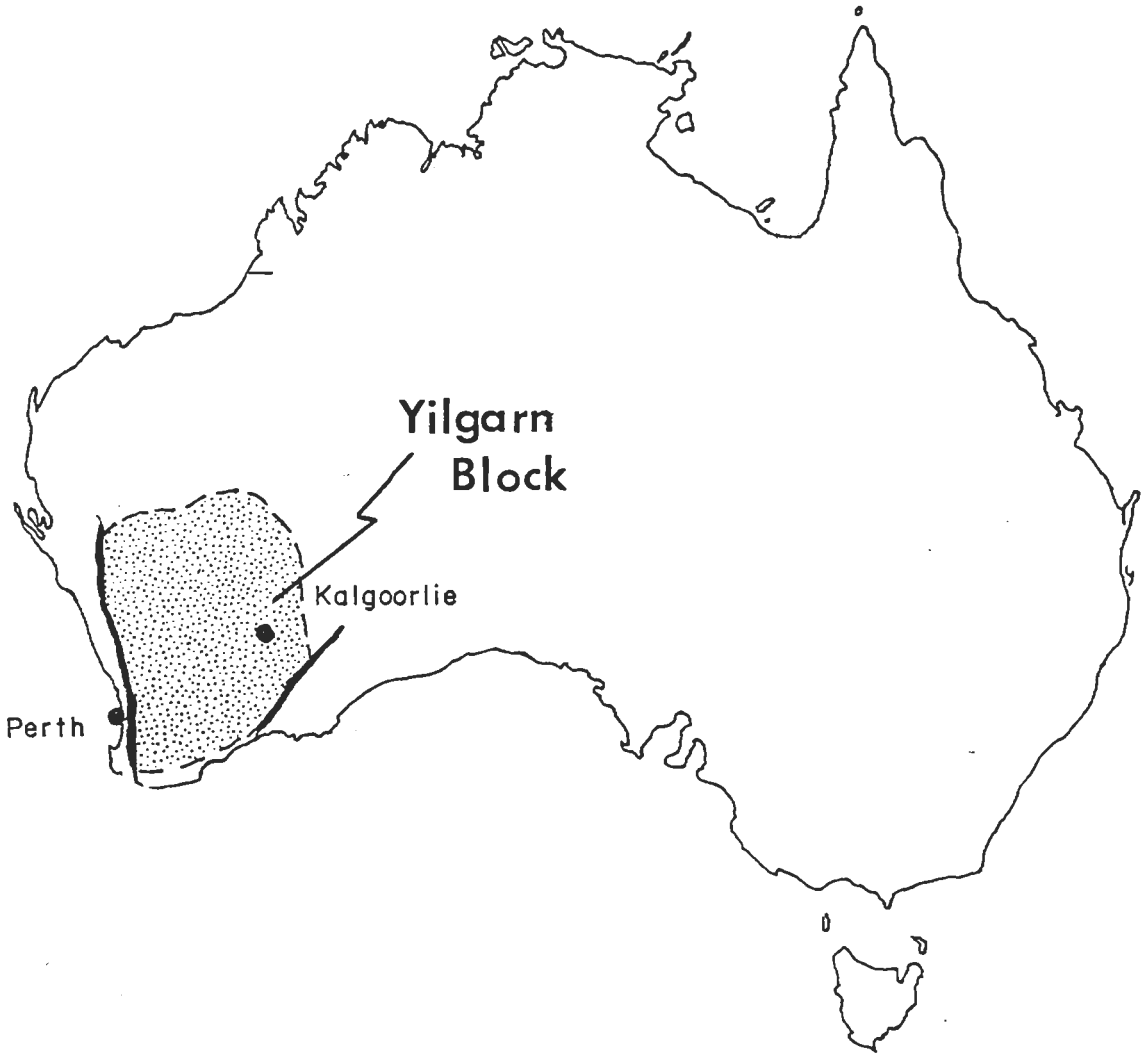

Fig. 1. Location of Yilgarn Block, Western Australia

1.1 FORMAT OF THESIS

The thesis is organized as follows:

Chapter one outlines the objectives, scope and analytical procedures used.

Chapter two describes briefly the geological environment in which nickel sulphide deposits occur with emphasis on the geology of komatiites. More detailed geological descriptions of each nickel province are given in the Appendices.

Chapter three discusses the results of the statistical analysis, describes how Mineralized and Barren komatiite geochemistry differs and the relative importance of each chemical variable.

Chapter four describes the chemical and geological characteristics of the volcanic and intrusive komatiite suites. Several examples from each suite are discussed in detail. The evaluation of the Windarra South geochemical results illustrates how geochemistry can assist in interpreting the internal structure of metamorphosed komatiite sequences.

Chapter five applies the chemical criteria derived in Chapters three and four to determine whether the Wonganoo-Bandjawarn greenstone belt is prospective for nickel sulphides.

Chapter six describes komatiites in the Southern Cross section of the Southern Cross-Forrestania greenstone belt and shows how they differ chemically from Forrestania komatiites. This is an example of regional differences in komatiite geochemistry.

Chapter seven evaluates the areas originally thought to be Barren but were classified as Mineralized by the discriminant analysis. This chapter also discusses the application of the geochemical and discriminant analysis criteria derived earlier to two new areas. One of these areas is shown to be highly prospective for nickel sulphides.

Chapter eight discusses the main results of the study and outlines some conclusions.

The Appendices include descriptions of the geology of three nickel provinces: Leonora-Wiluna; Kalgoorlie-Norseman and Windarra. Areas or groups of samples not discussed in detail in the text are also evaluated here. Supplementary descriptions of Mulvar - the computer program used in this study - and some of the analytical procedures are also included.

Not clear if analysed rocks were all collected by writer

1.2 DATA BASE

Three thousand three hundred (3300) samples of fresh rock komatiite ultramafic were collected and chemically analyzed during the period 1972 to 1974 inclusive. Data was obtained from 51 localities, representing possibly 80 komatiite sequences and several hundred (actual figure not known) individual komatiite intrusives and lavas (Table 1 and Fig. 2).

The chemical results for the groups listed in Table 1 are discussed in detail in Chapters 4 to 8 and in the Appendices. Kambalda, Windarra South, Trough Wells, Eureka greenstone belt, Red Well, Airport, Yilmia, Queen Victoria Rocks, Forrestania, Bullfinch and Mistake Creek are described in Chapter 4; Dingo Range West, Devines, Dingo Range East, Lalor North, Mt. Step and Colin Well are described in Chapter 5; Southern Cross drill holes, Marvel Lock A, Marvel Lock B, Marvel Lock C and Ennuin are described in Chapter 6; Area A, Yerilla, Mt. Jewel North, Heather Well, Area B and Area C are described in Chapter 7; and all remaining groups are described in the Appendices.

Samples were of four main types:

- Rock samples from mine openings.
- Pieces of drill core (about 5 cm long), selected at ten (3.05 m) or twenty foot (6.10 m) intervals. In some cases, wider spaced or random samples were used.
- Core pulps representing drill hole intervals of one to five feet (.30 to 1.52 m).
- Drill cuttings from rotary drill holes - each sample representing a five (1.52 m), ten (3.05 m) or twenty (6.10 m) foot interval.

The difference in sample types detracts from the data base to a small degree but does not affect the overall conclusions of the study. It is important, however, when comparing individual samples, or samples from drill hole to drill hole, if one hole has been sampled by core pieces and the other

MAJOR MINERALIZED GROUPS

CODE #	NAME
1	Forrestania
3	Windarra South
7	Windarra
13	Kambalda
25	Nepean
26	Scotia
50	Weebo Bore

MINOR MINERALIZED GROUPS

CODE #	NAME
2	Bouchers
4	Mt. Jewel
11	Trough Sells
16	Red Dam
19	Devines
20	Sir Samuel
27A	Marvel Lock A
34	Jubilee
46	Queen Victoria Rocks

BARREN GROUPS

CODE #	NAME
5	Eureka
6	Ennuin
8	Mistake Creek
9	Red Well
10	German Well
12	Area A
15	Yandel
17	Erlistown
21	Credo
24	Mertondale
27B	Marvel Lock B
27C	Marvel Lock C
28	Dingo Range West
30	Mt. Step
31	Lalor North
32	Colin Well
33	Dingo Range West
35	Bullfinch
36	Southern Cross
38	Mt. Jewel North
39	Heather Well
40	Airport
41	South Bullong
42	Yerilla
48	Wongi South
51	Yilmia Hill

UNCLASSIFIED

CODE #	NAME
22	Area B
47	Area C

TABLE 1 - Code numbers and names of all groups of komatiites referred to in this study.

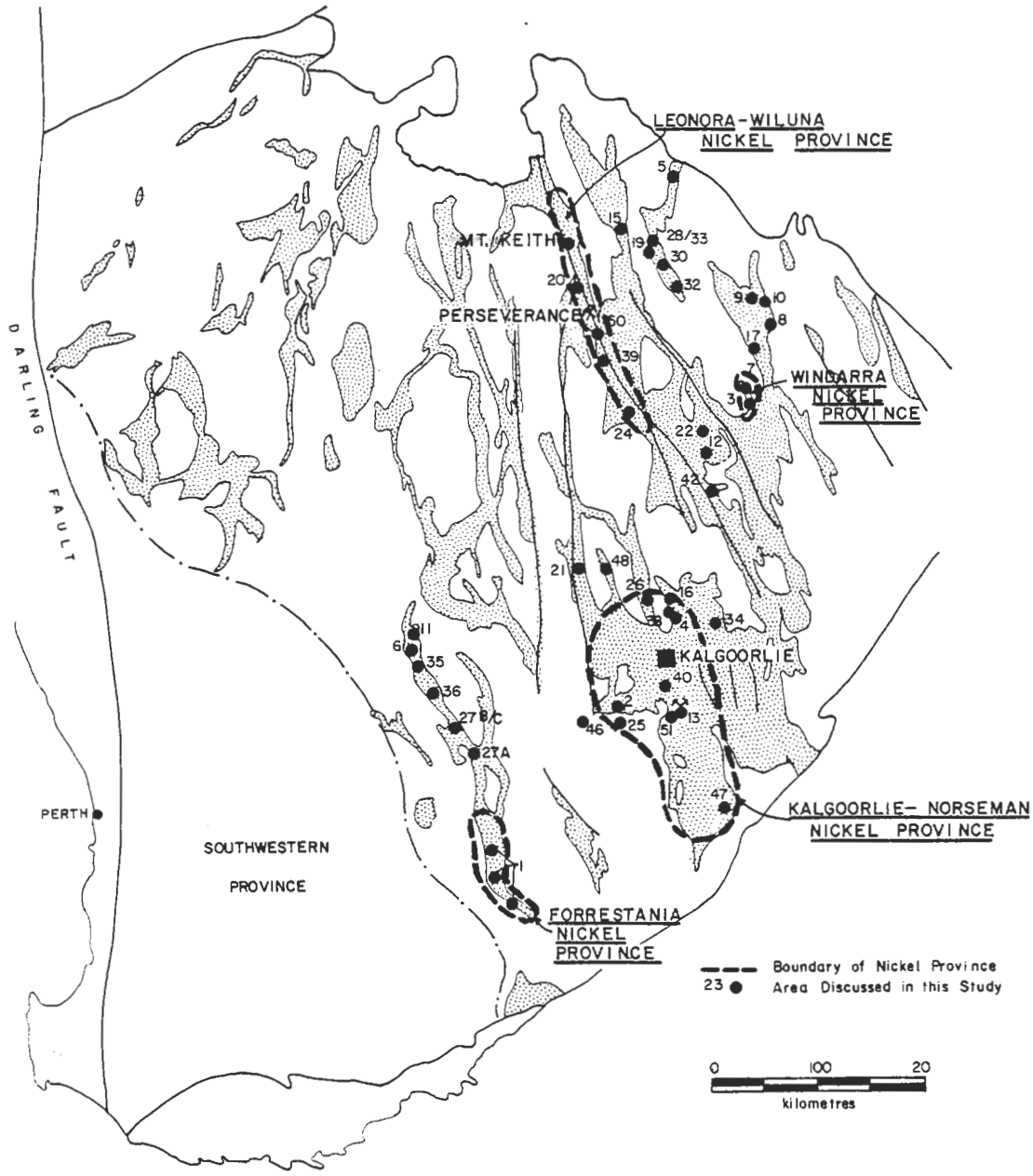

Fig. 2. Yilgarn Block, showing distribution of "greenstone belts", location of four nickel provinces, and approximate locations of komatiite sequences sampled, (for area names refer to Table 1).

using core pulps. The core pulps give an average value, whereas pieces give a point value, and this is significant when dealing with komatiite lavas.

Chemical variables were selected from elements known to be an integral part of ultramafic rocks, and from elements thought to be indicative of sulphide mineralization. Important limiting factors in deciding which elements could be used were the type of chemical analysis required for any determination and the cost of the analysis. Major rock forming elements selected were calcium, magnesium, iron and aluminium; minor elements included chromium, titanium and manganese; and elements associated with mineralization were nickel, copper, zinc and cobalt. The partial extractions of nickel, copper and cobalt designated Ni$\underline{P}$, Cu$\underline{P}$ and Co$\underline{P}$ respectively, were included because Cameron, et al. (1971) showed them to be of possible value in determining mineralization potential. Sulphur and vanadium were analyzed in the first 407 samples.

1.3 ANALYTICAL PROCEDURES

Most analyses were carried out in a mining company laboratory using procedures specifically designed, or modified, for this program. Analytical precision was controlled by the use of a number of external and internal reference samples. The reference samples consisted of both synthetic samples and ultramafic rock pulps, with a wide variety of chemically and geologically different matrices, and were obtained from the U.S.G.S. (standards ref. G-2, GSP-1, AGV-1, PCC-1, DTS-1, BCR-1); Canadian Dept. of Mines (Ultramafic ref. standards - UM1, UM2, UM4); La Trobe University (ANU27183, ANU23182); Victorian Mines Dept. (USBS 99); and Townser and Mersor (BCS 175/2 - iron ore standard).

Townsend + Mercer ?

The partial extractions of nickel copper and cobalt were carried out using a cold leach technique which employed a mixture of ascorbic acid and hydrogen peroxide (Lynch 1971), followed by atomic absorption spectrometry. According to Smirnova et al. (1968) and Cameron et al. (1971) this method is specific for the sulphide fractions of each metal in ultramafic rocks. Cameron et al. (1971) also state that only minor quantities of the metals (less than 5%) are leached from silicates during this process, although if serpentinization has taken place in the ultramafic samples, it may be that greater amounts are leached. Throughout this study, this extraction method is referred to as a partial extraction in preference to a sulphide extraction.

Which is generally the case !

The total extractions for nickel, copper, aluminium, calcium, magnesium, zinc, chromium, manganese and cobalt were obtained using 50 percent hydrofluoric acid in combination with 70 percent perchloric acid leach (one solution), and atomic absorption spectrometry. This extraction proved to be a total extraction except where chromite was a significant component of the sample. The leach dissolved some but not all of the chromium present. Thus the Cr procedure was in certain instances a partial analysis and is essentially a measure of the Cr in the lattice of the silicate minerals or

Cr attached to sulphides.

Approximately 200 representative samples were independently reanalyzed for total Cr, using a sodium peroxide fusion technique. Samples from mineralized komatiites at Windarra South and Forrestania averaged 7 percent lower than the original values; samples from unit 2 at Windarra South averaged 110 percent higher; samples from Red Well averaged 35 percent higher. Thus in most mineralized ultramafics, the hydrofluoric/perchloric leach apparently extracted 100 percent of the chromium whereas in barren ultramafics, it extracted between 40 and 100 percent of the chromium.

BUT WINDARRA SOUTH IS MINERALISED

The Cu, Ni, Zn, Mn and Co values were reproducible to better than 5 percent relative error. The Ca, Mg, Al, Ti, Fe and Cr values were reproducible to within 10 percent relative error and except for Cr and Al can be regarded as very close to true values analytically. The partial extractions of Cu (Cu$\underline{P}$), Ni (Ni$\underline{P}$) and Co (Co$\underline{P}$) are reproducible to within 5 percent relative error.

Values for all elements throughout this study and in all tables are expressed in parts per million except for Ca, Mg, Fe, Al, S and TiO_2 for which values are given in percentages. All analyses are on a "volatile included" basis unless otherwise stated.

CHAPTER 2

2. GEOLOGICAL ENVIRONMENT

The nickel sulphide deposits to which this study is relevant occur within the Eastern Goldfields Province (Williams 1974) of the Archaean Yilgarn Block (Trendall 1975) of Western Australia. The location of nickel provinces and areas studied are shown on Fig. 2. Additional description of the geology of some nickel provinces is included in Appendices 1, 2 and 3.

2.1 TOPOGRAPHY AND WEATHERING

The Yilgarn Block has been peneplaned to a very subdued topography at a general altitude of between 300 and 600 m, with a relief of approximately 50 m. The area is characterized by poor outcrop, oxidation and surface leaching, extensive areas of transported soils and laterite, and the superimposed effects of many weathering cycles. In the southeastern part of the Yilgarn Block basic rocks tend to outcrop as long, low, narrow ridges and weathering effects are somewhat less severe than in the northern half of the Block. North of Menzies (latitude 30 degrees south), major landscape elements are scarps (breakaways) and their complementary pediments strewn with gibbers (gravels). Sheet wash is a major erosional process. Two main erosional surfaces are present; the upper is dominant, and coincides with the top of the laterite, and is considered to be Early Tertiary or Cretaceous (Morgan 1966). Laterite is extensive, overlain in places by siliceous and indurated gravel. Ultramafic rocks are very poorly exposed and seldom outcrop except as rubbly exposures between hills of more resistant mafic rocks or adjacent to salt lakes where recent erosion has stripped off older weathered material. In many areas, indications of ultramafic rocks, if they are present at all, consist of surface deposits of opaline silica, chalcedony, magnesite, and silicified talcose fragments.

The highly weathered mantle of the Yilgarn Block and the extensive development of laterite and lateritic soils which are different chemically from the parent rocks, constitute a severe barrier for nickel sulphide exploration. Exploration methods to date have emphasized "gossan search" (detailed search for fragments or small outcrops of limonitic material), soil geochemistry in areas of residual or mainly residual soils, "bedrock geochemistry" and induced polarization surveys. By far the most effective method is bedrock geochemistry. This method uses auger, rotary or percussion

drills to sample subsurface weathered rock. Sampling points are usually spaced at 15 or 30 m intervals at right angles to the strike of an ultramafic. Hole depths required may vary from a meter to 50 m. Even in areas of residual soil, leaching may be intense enough in parts of the laterite profile to remove all traces of nickel in weathered ultramafics for depths of 15 to 50 m. Detailed exploration is thus expensive and time consuming.

2.2 GREENSTONE BELTS

The Archaean of Western Australia consists largely of volcanogenic and volcanoclastic rocks, or greenstone belts (Fig. 2), extensively intruded by granitic rock. These belts are composed of ultramafic rocks; mafic and felsic volcanic rocks and intrusives; volcanoclastic sediments; cherts; graphitic and/or sulphidic shale; banded iron formation; and arenacous and conglomeratic rocks.

Archaean greenstone and sedimentary belts can be envisaged as elongate, or irregularly lensoid, keel-like bands of volcanics and sediments, immersed in a sea of granitic and gneissic rocks. Many of the mafic flows are pillowed, which together with the evidence of interflow sedimentation, suggests that most if not all of the volcanism took place in a marine environment. There is evidence of cyclic volcanism in many greenstone belts, from basic volcanism in lower members to acidic (rhyolitic) volcanism towards the tops of assemblages. Some of the basic members are characterized by an abundance of ultramafic rocks which are typical of the komatiite suite (Naldrett and Cabri 1976). Intrusions of gabbro, diorite and dolerite are present in all belts and form regular or irregular sills, dykes and ramifying masses. Quartz feldspar porphyry dykes are ubiquitous to many localities. The youngest intrusive rocks are dykes, stocks and batholithic masses of granitic rock with associated pegmatite, which were apparently derived during granitization and development of gneissic rocks. All greenstone belts have been extensively folded, faulted and sheared and most are structurally complex.

Two rock types besides ultramafic rocks deserve particular mention - banded iron formation and sulphide-rich black shales. Several facies of banded iron formation are recognized of which the oxide and sulphide are the most important within the Yilgarn Block. The oxide facies consists of alternating highly contorted bands of variously coloured chert, magnetite

and/or hematite. The sulphide facies is represented by banded pyrrhotite (pyrite in zones near the surface), with minor base-metal sulphide minerals. Sulphidic black shales are commonly interbedded with mafic volcanic and ultramafic flows. They probably represent periods during which reducing, sapropelic conditions prevailed. The shales vary from a few centimeters to tens of meters in thickness, and often extend for some kilometers along strike. They exhibit fine scale bedding and bedding convolutions and consist of fine-grained pyritic and graphitic layers, interbedded with cherty or siliceous layers. In some cases pyrite is not visible megascopically, but microscopically is present in abundance. Sulphides include pyrite, pyrrhotite, chalcopyrite, arsenopyrite, galena and sphalerite and in rare instances chalcopyrite and sphalerite may be concentrated to give copper and zinc contents of several percent. Some of these sulphide rich sediments appear to be spatially related to nickel sulphide mineralization, in that nickel sulphides may occur in equivalent stratigraphic positions to pyritic sulphide sediments, along strike.

2.3 KOMATIITES

Ultramafic and related rocks have been grouped and classified by Naldrett (1973) and Naldrett and Cabri (1976) according to tectonic setting, size, form and chemical composition. Most of the ultramafics in the Yilgarn Block are komatiites and belong to the synvolcanic orogenic suite of Naldrett and Cabri (1976).

The name komatiite was coined by Viljoen and Viljoen (1969), for ultramafic rocks well developed in the Komati River area of the Barberton Mountain land. Naldrett and Cabri (1976) redefined komatiites into the following suite members (Table 2): dunite (40 wt. percent MgO calculated on an anhydrous basis); peridotite (30 to 40 percent MgO); pyroxene peridotite (20 to 30 percent MgO); pyroxenite (12 to 20 percent MgO); and magnesium basalt (10 to 12 percent MgO) to basalt (less than 10 percent MgO). The ultramafic members of the suite were, according to Naldrett and Cabri (1976), derived from liquid containing up to 40 percent MgO.

Settling and accumulation of the olivine phenocrysts, coupled with filter pressing, compaction and some adcumulus growth, were responsible for the peridotites and dunites (Naldrett and Turner 1977). Platy and skeletal growth of the olivine and clinopyroxene crystals characterize the upper parts of some flows or intrusives and is known as spinifex texture (Nesbitt 1971). Spinifex zones alternate with zones of olivine peridotite or peridotite (characterized by equant olivine textures) which form the basal sections of individual komatiite units. Nesbitt (1971) suggests that spinifex textures are the result of rapid, in situ, crystallization of a silicate liquid.

Naldrett and Cabri (1976) indicated that komatiites can be distinguished from ultramafics derived from a tholeiitic parent liquid, by both Al_2O_3 vs $FeO/(FeO+MgO)$ and TiO_2 vs MgO plots (Fig. 3). Total Fe in the rocks is calculated as FeO. All West Australian komatiites except Enniun (6) plot

	1	2	3	4	5	6	7
SiO_2	40.2	44.0	47.6	48.9	51.0	52.2	n.d.
Al_2O_3	0.29	5.27	6.19	10.3	12.6	14.8	4.0
TiO_2	0.02	0.27	0.33	0.5	0.59	0.80	0.2
Fe_2O_3	7.89	12.2	10.4	12.3	12.6	11.53	n.d.
MnO	0.39	0.22	0.22	0.23	0.4	0.2	0.14
MgO	51.6	35.5	27.7	16.5	10.68	7.95	32.5
CaO	0.04	5.48	6.88	9.78	10.54	10.17	3.9
Na_2O	0.01	0.32	0.19	1.18	2.35	2.44	n.d.
K_2O	0.01	0.04	0.11	0.13	0.13	0.28	n.d.
Total	100.44	100.30	99.46	99.82	100.70	100.36	n.d.
Fe as FeO	7.10	10.95	9.38	11.07	11.31	10.36	9.2
Ni	nd	nd	nd	nd	nd	nd	1870ppm
Cu	nd	nd	nd	nd	nd	nd	40ppm
Zn	nd	nd	nd	nd	nd	nd	72ppm
Cr	nd	nd	nd	nd	nd	nd	1930ppm
Co	nd	nd	nd	nd	nd	nd	119ppm

1. Dunitic komatiite — Naldrett & Turner (1977)
2. Peridotitic komatiite (spinifex texture) — Naldrett & Turner (1977)
3. Pyroxene peridotitic komatiite (spinifex texture) — Naldrett & Turner (1977)
4. Pyroxenitic komatiite — Naldrett & Turner (1977)
5. Magnesian basaltic komatiite — Naldrett & Turner (1977)
6. Basaltic komatiite — Naldrett & Turner (1977)
7. Average komatiite, this study recalculated on an anhydrous basis — McNeil

Table 2. Typical komatiite analyses from Naldrett and Turner (1977). Mean values for komatiites from this study are included for comparison. Al_2O_3, TiO_2, FeO, and CaO values fall between dunitic komatiite and peridotitic komatiite of Naldrett and Turner (1977), whereas MgO is between peridotitic komatiite and pyroxene peridotitic komatiite. Naldrett and Turner's MnO values are considerably higher than those of this study.

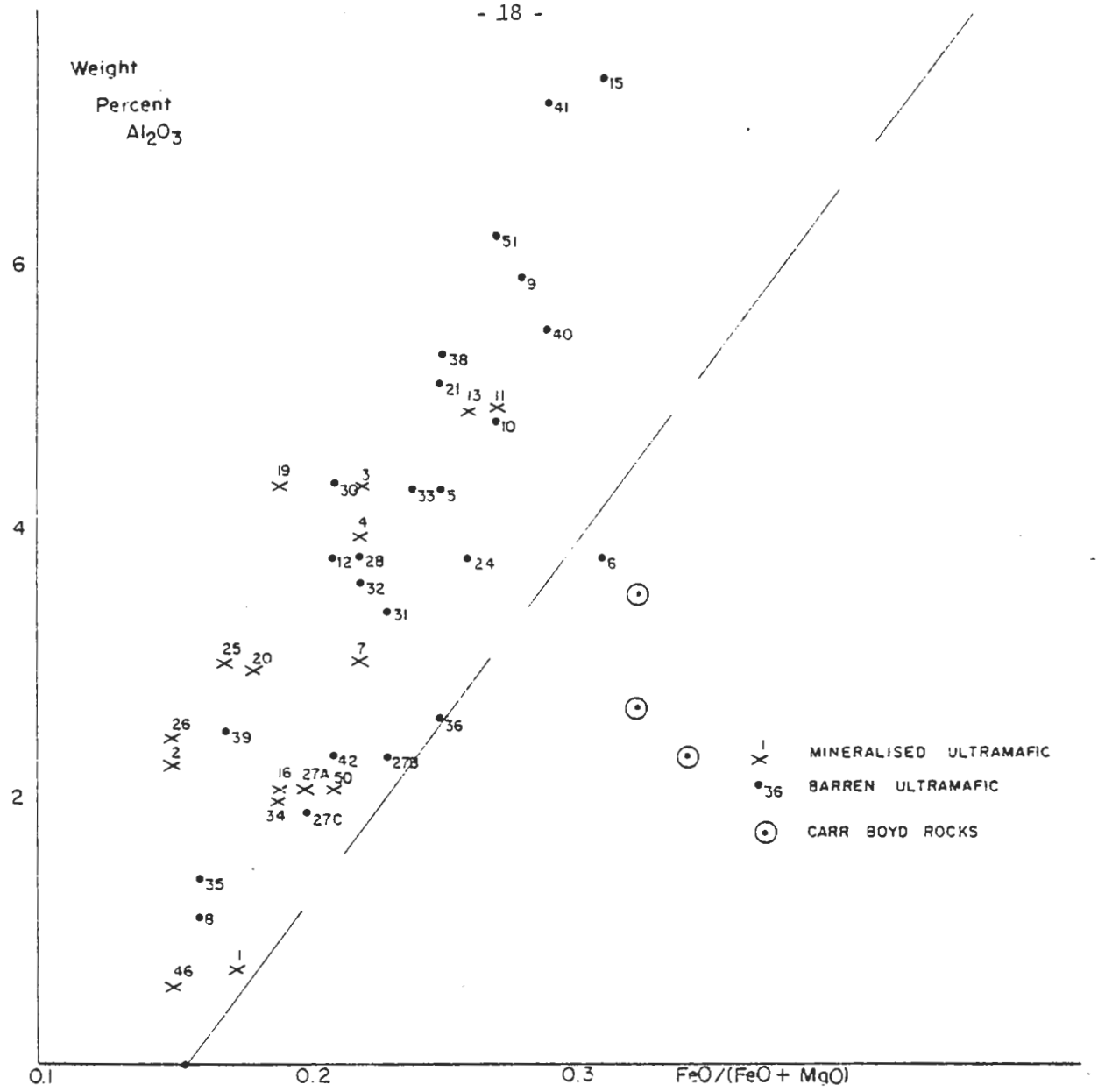

Fig. 3. Plot of Al_2O_3 against FeO/FeO+MgO for mean values of all sample groups in this study. The dashed line represents the dividing line between ultramafics with komatiite and tholeiite parent magmas, according to Naldret and Cabri (1976). Although Ennuin (6) falls into the tholeiitic section, based on its geologic context and TiO_2 content, it appears to be a genuine komatiite. Carr Boyd Rocks represent an ultramafic with tholeiitic parentage.

THIS DIAGRAM ESSENTIALLY USES Fe/Mg AS A DISCRIMINANT
Al_2O_3 IS SUPERFLUOUS & CaO, TiO_2, P_2O_5 Zr etc COULD
HAVE BEEN USED. WHERE DOES MORB PLOT ?

within the field appropriate to Naldrett and Cabri's komatiite grouping. Data for three ultramafics from Carr Boyd Rocks (Purvis et al. 1972) which represent a tholeiitic parent magma, are also shown for comparison. The komatiite suite is unique among ultramafic rocks in that it appears to be restricted to Archaean greenstone belts. There is an apparent contrast between ultramafic liquids generated in the Archaean, and those developed later, and this may be an indication that a particular stage of mantle and/or crustal development was reached in the Late Archaean, Lower Proterozoic Period. Nesbitt (1972) suggested the term "Archaean greenstone peridotite" be used for this particular ultramafic suite. Komatiite is considered preferable as the ultramafics are a suite of rocks and are not confined to peridotites.

2.4 METAMORPHISM AND ALTERATION

Binns et al. (1976) recorded a wide range in metamorphic grade throughout the eastern Yilgarn Block and delineated four types of metamorphic domain (low greenschist facies to mid to high amphibolite facies). They also recognized two contrasting styles, designated static style where primary structures and textures are preserved, and dynamic style which is characterized by penetrative foliations and lineations. Static style is usually present in the lower grade metamorphic domains and dynamic style in the higher grade domains.

Barrett et al. (1977) maintain that at least some nickel ores (i.e. the more massive sulphides) have been concentrated by metamorphic process and suggest that all massive sulphides may have been generated from more disseminated sulphides during metamorphism. There is no doubt that metamorphic and deformational processes played a significant role in the evolution and mobilization of some massive sulphide lenses, particularly at Redross, Perseverance and Nepean. However, as the great bulk of massive sulphides occur at Kambalda, in a relatively low grade metamorphic domain (low amphibolite - static style according to Binns et al. 1976) it seems more probable that the massive ores resulted from a separate intrusion of magmatic sulphide liquid (Ross and Hopkins 1975), and that later metamorphism merely modified and in some cases remobilized the massive sulphides.

Widespread hydration and carbonation are associated with many komatiites and pervasive serpentinization has obliterated most original textures. In some areas such as at Lunnon (Kambalda), Ross and Hopkins (1975) concluded that talc-carbonate alteration was widespread and serpentine rocks simply represent portions of the komatiite sequence which escaped alteration. At Mt. Monger, Williams (1971) suggested that talc-carbonate alteration is also later than serpentinization and that its distribution within an ultramafic

body was directly controlled by the presence of CO_2 during metamorphism, and was unrelated to the original ultramafic rock. Within any one body the change from serpentinite to talc-carbonate occurs over a short distance, but is gradational. The carbonate material is usually a sidero-magnesite (e.g. 49.1% Mg, 11.2% Fe, 0.6% Ca). Where talc-carbonate alteration is complete, no original rock textures are retained. Ross and Hopkins (1975) concluded that there is a loss of CaO from peridotite from both serpentinized and talc-carbonate assemblages, and that the loss took place during serpentinization. During serpentinization practically all anhydrous mafic minerals of igneous origin were reconstituted to the lizardite-chrysotile-brucite, actinolite-chlorite, albite-epidote-clinozoisite, and prehnite suites. Equilibrium of mineral assemblages throughout the entire rock was generally not achieved. Antigorite bearing serpentinites are a progressive metamorphic alteration product of the lizardite assemblage.

In medium to high amphibolite facies domains, regenerated olivine dominates the more magnesium rich komatiites. Secondary olivine is derived by the breakdown of earlier serpentine talc-carbonate assemblages. Commonly, the dehydration of antigorite results in a crystalloblastic intergrowth of elongate olivine crystals set in a talcose matrix which superficially resembles spinifex texture.

In most dynamic style terrains, much, if not all of the original rock fabric and textures, such as spinifex texture, have been obliterated. Consequently, it is often difficult to determine from scattered and rare surface outcrops whether the ultramafics are intrusive or volcanic, and the thickness and composition of individual units. Also, because changes during serpentinization and carbonate metasomatism involve changes in Mg to Si ratio, and in Ca content, an abundance of metamorphic olivine need not necessarily imply a dunitic parent.

All Mg analyses in this study were determined on a hydrous basis and thus Mg analyses are not directly comparable between low grade metamorphosed, serpentine rich komatiites and medium-high grade metamorphosed, regenerated olivine rich komatiites. The latter will always have a higher Mg content.

This Mg anhydrous factor is a major problem. ~~From case~~
What does Table 3 mean in terms of "Mean Mg" if
Loss is unknown ?

2.5 GEOLOGICAL SUBDIVISION OF THE YILGARN BLOCK

Trendall (1975), Williams (1974) and Gee (1975) subdivided the Yilgarn Block into geological provinces and subprovinces (Fig. 4). Trendall (1975) defines a province as "an area of the earth's crust in which the rocks have some geological character, or combinations of characters in common; these are usually either age, metamorphic grade, structural style or type of mineralization." Trendall (1975) subdivides the Yilgarn Block into three major provinces, namely the Southwestern, Murchison and Eastern Goldfields. The Southwestern Province appears to be a valid subdivision on the basis of higher metamorphic grade (granite migmatite terrain occupies 95% of the province); absence of economic mineralization (either gold or nickel); and perhaps to a lesser extent on the fact that parts of the province have yielded age dates greater than 3,000 m.y. The Murchison Province, according to Trendall (1975), is characterized by a dominant east-northeast trend, and Gee (1975) by ovate cellular granite plutons. The Eastern Goldfields Province is characterized by north-northwesterly trends (Trendall, 1975); by an overall northerly trend (Gee, 1975); and by the larger size of volcanogenic belts, and the discrete nature of individual granitic plutons (Gee, 1975). De la Hunty (1975), however, states that the geology of the Murchison Province is basically similar to that of the Eastern Goldfields Province.

The above geological criteria are ambiguous and do not provide an adequate geological basis on which to separate the Murchison and Eastern Goldfields Provinces. The names are useful in terms of geographic areas, but on the basis of present geological data they are not separate and distinct geological provinces. For instance, Gee (1975) cites north to northeasterly trends for the Murchison and overall northerly trends for the Eastern Goldfields. Superficially there would appear to be little difference between these two sets of trends. In fact, in the southern half of the Murchison Province, trends can

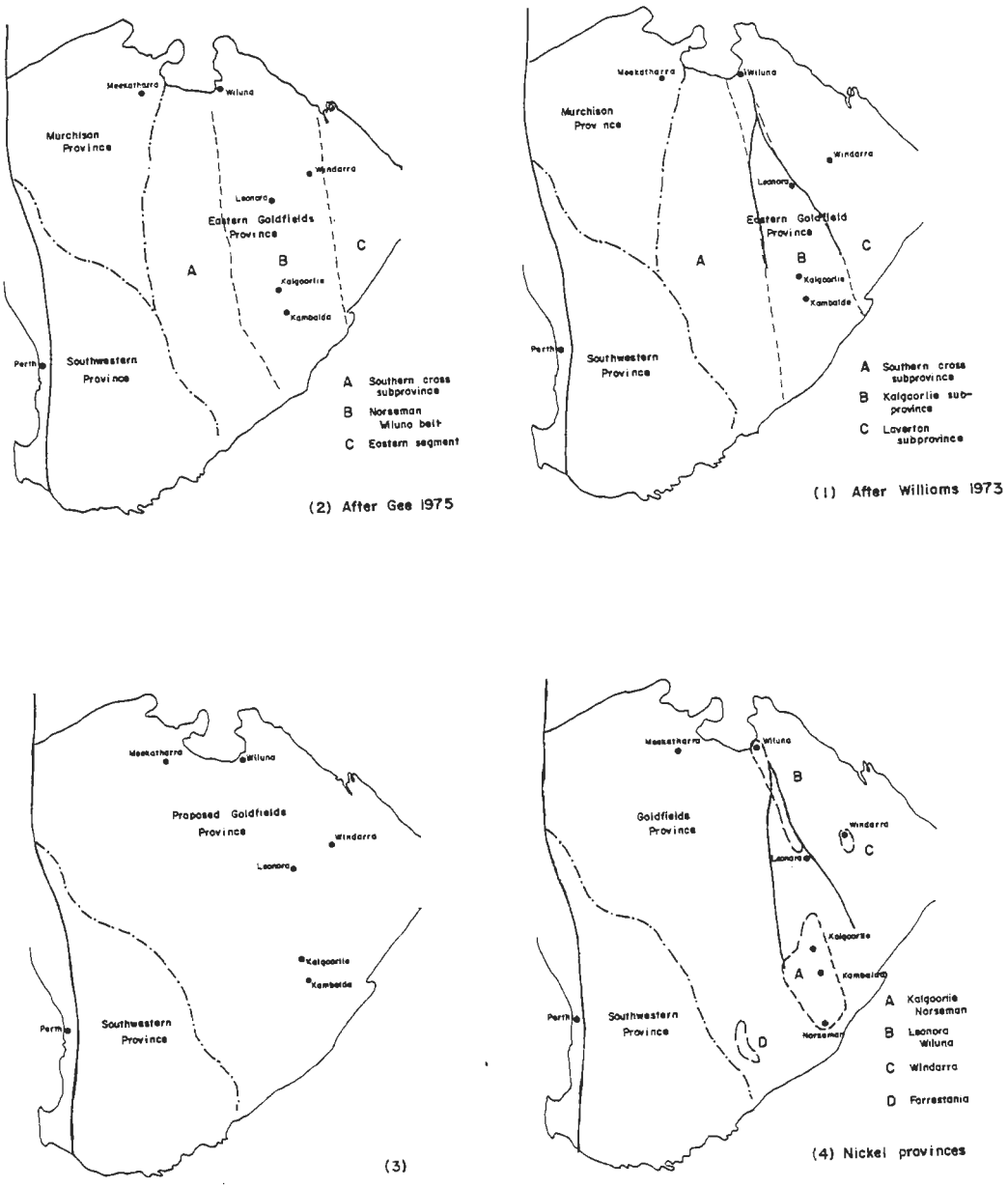

Fig. 4. Proposed geological and nickel metallogenic provinces within the Yilgarn Block of Western Australia.

(1) After Williams (1974), geological subdivision
(2) After Gee (1975), geological subdivision
(3) After McNeil, this paper, geological subdivision
(4) Proposed nickel provinces, McNeil, this paper.

be interpreted as mainly northerly to slightly west of north, and only in the northern half of the province can trends be said to be dominantly north-northeast or northeast. In the Eastern Goldfields Province the dominant trend is north-northwest in the Norseman-Wiluna belt (Gee 1975) but even here there are numerous exceptions. In the Diemals-Barlee area (the western section of the Eastern Goldfields Province) the dominant trend varies from northeast to northwest. Dominant trends are subject to interpretation and are not sufficient basis in this case to separate geological provinces. Other suggested differences such as cellular granite plutons (Murchison) and discrete individual granite plutons (Eastern Goldfields) do not appear to be sufficiently definitive. The larger size of the volcanogenic belts (or perhaps it should be expressed as the ratio between granitic and non-granitic rocks) is valid to the extent that the ratio of granitic rocks to non-granitic rocks in the Kalgoorlie-Kurnalpi Norseman and Leonora-Laverton-Agnew triangles is considerably less than in the Murchison Province. This distinction, however, is not valid for the whole Eastern Goldfields Province.

It should not be inferred from this argument that significant differences do not occur between various parts of the Yilgarn Block, outside the South-west Province. There are differences but the two suggested major divisions are not considered to be logical subdivisions. It is suggested here that the whole region (Murchison plus Eastern Goldfields) should be assigned province status and renamed the Goldfields Province (Fig. 4). This Goldfields Province could then be subdivided into at least seven and perhaps more subprovinces.

Williams (1974) divided the Eastern Goldfields Province into three subprovinces, namely the Southern Cross, Kalgoorlie and Laverton: Gee (1975) suggested that the province be divided into the Southern Cross subprovince and two other areas which he designates as the Wiluna-Norseman belt and the Eastern segment. However, the Southern Cross subprovince places together several areas with widely divergent structural and petrological domains.

Contrasting characteristics within the subprovince are that large layered gabbroic intrusives which contain anorthosites and titaniferous, vanadiferous magnetite layers, occur only in the northern segment; highly magnetic and thick banded-iron formations and lack of a consistent structural trend characterize the central part; and linear, thin greenstone belts with associated gold and, in part, nickel mineralization are present in the southern part.

One of the characteristics of the Kalgoorlie subprovince of Williams (1974) and an implied characteristic of the Wiluna-Norseman belt of Gee (1975), is the concentration of nickel sulphide deposits within these areas. In fact, mineralization in terms of total nickel metal in sulphides, or total volume of suphides within ultramafics, is concentrated in four widely separated areas: Perseverance-Mt. Keith; Windarra-Windarra South; Kambalda and Forrestania. Scattered but small occurrences of nickel sulphide occur in the Coolgardie-Norseman area.

Both Williams (1974) and Gee (1975) have made credible attempts to subdivide the Yilgarn Block into separate geological units. The writer suggests that the evidence presently published to support these subdivisions is tenuous and in many areas subject to alternative interpretations. To accept these divisions unquestioningly at this stage in our knowledge will inhibit geological and mineral exploration progress. It may be that certain subdivisions such as the Wiluna-Norseman belt are more appropriately defined as provinces, rather than subprovinces. In these circumstances the Murchison Province could be retained. Whether or not the elevation of the Wiluna-Norseman belt to province status, or the redefinition of the Murchison and Eastern Goldfields Provinces as one province (Goldfields Province) is accepted, smaller areas than those defined to date as subprovince should be used in future. For example, the Bullfinch-Forrestania area, the Leonora-

Wiluna belt, the Kalgoorlie-Kurnalpi-Norseman triangle, are more logical subdivisions at the present state of geological knowledge.

It was considered necessary to briefly consider the geologic subdivision of the Yilgarn Block because of genetic implications in relation to nickel. Other authors have stated that known nickel sulphide deposits occur mainly in the Eastern Goldfields Province; are concentrated in the Wiluna-Norseman belt or Kalgoorlie subprovince; and are not known to occur in the Murchison Province. From this it must not be inferred that nickel exploration should only be carried out in the Kalgoorlie subprovince. There is still insufficient information available to exclude from prospecting komatiites in other parts of the Yilgarn Block.

2.6 NICKEL PROVINCES

Four nickel provinces (Fig. 2) can be defined within the Yilgarn Block on present geological knowledge. They are: Leonora-Wiluna, Kalgoorlie-Norseman, Forrestania and Windarra. The Leonora-Wiluna and Kalgoorlie-Norseman are major provinces and Forrestania and Windarra are minor provinces. A province is defined as a geographic clustering of nickel sulphide occurrences within an area of relatively uniform geology.

The Leonora-Wiluna Province contains mineralization predominantly in large intrusive komatiites, which appear to be related to a major crustal break known as the Keith-Killkenny lineament. The deposits change in tenor of mineralization and character from north to south. At the northern end of the province low grade, large disseminations are present, but with distance south, grade and sulphide concentration increases and at the southern end of the province at Mt. Clifford, the deposits have "volcanic" affinities.

The Kalgoorlie-Norseman Province is a large geographic area (160 by 240 km.) with many small individual nickel sulphide accumulations. The deposits belong to the volcanic suite and are relatively high grade. Massive sulphides are a feature of most occurrences. The ratio of granitic to other rocks within this province is much less than in other nickel provinces.

The Forrestania Nickel Province is a narrow, linear province approximately 40 km. in length. Nickel sulphide deposits are relatively small and occur within an intrusive suite of ultramafics. This province has more similarities with the Leonora-Wiluna Province than with the Kalgoorlie-Norseman Province.

The Windarra Nickel Province is a small narrow province which contains two main and several minor sulphide occurrences. The komatiites are a part of a volcanic suite, similar to the ore hosts in the Kalgoorlie-Norseman Province.

The geology of the Leonora-Wiluna, Kalgoorlie and Windarra provinces is described in greater detail in the appendices. The Forrestania province is described in Chapter 4.

CHAPTER 3

3. MINERALIZED AND BARREN KOMATIITES

The multivariate analysis program used to evaluate the chemical data provided a discriminant analysis, principal component analysis, mean chemical values by group and correlation co-efficients (Mulvar-Geostatistics, Perth, Australia). Discriminant analysis proved to be the most effective statistical method.

It was assumed that samples of fresh rock komatiite could be designated Mineralized or Barren from their known geological context. Samples could be designated Mineralized with accuracy, but this may not be true for all samples designated Barren. Most samples of non-mineralized komatiites came from isolated, or less intensely prospected and drilled areas, and thus the geologic context was not always known with certainty. For the statistical analysis it was assumed the Mineralized komatiites and Barren komatiites are distinct and separate groups. The data base used in the statistical analysis consisted of 2786 samples from 40 localities - seven major mineralized areas, nine minor mineralized areas and twenty-four barren areas. A total of 1320 samples were designated as Mineralized and 1456 as Barren.

3.1 MEAN GEOCHEMICAL RESULTS FOR EACH LOCALITY

Mean values and standard deviations by group, for each of the thirteen chemical variables used in Discriminant Analyses A, B and D are listed in Table 3. Caution must be exercised in the evaluation of these results because most groups do not represent individual komatiites, but are composed of many separate intrusions or lavas. Within a volcanic komatiite suite, geochemical signatures can, and usually do change in different parts of the pile.

There is considerable overlap in mean values, when standard deviations are considered, between groups classified as either Mineralized or Barren. However, Ni, NiP and Mg values are higher in mineralized groups (means of 1027 ppm, 2220 ppm and 19.2 percent respectively) than in barren groups (means of 429 ppm, 1530 ppm and 16.4 percent respectively). The reverse is true for chromium (1617 ppm in mineralized groups and 2260 ppm in barren groups). There are less pronounced differences such as higher CoP and lower Mn, Fe and Zn in mineralized groups than in barren groups. All differences, because of overlapping standard deviations, are not in themselves sufficient to differentiate between the two populations. The geometric mean of each variable, for both populations, is included for reference. The difference between the arithmetic and geometric means is a measure of the variance in the data, for each variable.

Within the mineralized groups, intrusive suites such as Forrestania have high Ni, Mg and low Cr relative to volcanic suites such as Kambalda, Trough Wells and Windarra South. These differences are partly caused by the fact that in the volcanic suites, samples were obtained not only from the nickel sulphide host komatiite, but also from numerous overlying komatiite lavas. A second cause is the fact that there is considerably more chemical variation within sulphide host komatiites from volcanic suites than from intrusive suites.

Each group listed in Table 3 is evaluated in detail later in this thesis or in the Appendices.

A. Mineralized Ultramafics

Map Area	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co
1	1348(1013)	2980(1028)	24(48)	28(51)	0.4 (0.4)	1.2 (1.7)	24.0(4.0)	54(21)	1076(651)	866(241)	6.5(1.2)	54(29)	126(23)
3	1112(1086)	2030(1214)	50(52)	57(56)	2.3 (1.5)	3.1 (2.2)	15.6(3.6)	97(53)	1720(656)	1196(418)	5.7(1.5)	50(36)	112(32)
7	1192(959)	2244(1171)	38(44)	44(46)	1.6 (1.)	2.0 (2.3)	16.1(3.5)	79(54)	2539(853)	1056(565)	5.7(1.8)	58(34)	122(39)
13	456(644)	1439(653)	46(27)	53(30)	2.6 (0.9)	3.6 (1.7)	14.7(3.2)	67(21)	1958(559)	1237(262)	6.8(1.1)	30(18)	109(13)
25	1160(799)	1789(429)	17(25)	57(10)	1.6 (1.0)	1.7 (1.8)	20.8(5.4)	44(29)	1243(815)	993(372)	5.5(1.6)	56(52)	120(52)
26	2421(2157)	3391(1847)	36(24)	37(23)	1.3 (0.3)	0.3 (0.3)	23.9(2.0)	68(21)	1150(1501)	764(177)	5.5(0.3)	59(31)	133(24)
50	4569(2090)	5179(2210)	174(85)	195(87)	1.1 (1.3)	0.5 (1.1)	20.1(3.7)	72(28)	1950(905)	1000(404)	7.1(1.0)	91(53)	175(51)
2	709(337)	2329(590)	12(26)	16(29)	1.2 (1.0)	1.2 (1.6)	23.0(5.2)	50(18)	1447(525)	905(236)	5.3(1.2)	36(16)	114(17)
4	868(434)	1901(605)	30(53)	34(50)	2.1 (1.3)	2.5 (1.8)	18.9(4.4)	78(36)	1625(494)	1066(267)	6.7(1.0)	50(21)	120(15)
11	635(471)	1418(586)	25(39)	25(36)	2.6 (1.2)	3.9 (2.1)	16.1(3.6)	79(21)	2085(684)	1352(350)	7.8(1.5)	42(32)	125(30)
16	2136(794)	2636(618)	48(47)	49(48)	1.1 (0.7)	1.6 (1.6)	19.6(2.2)	50(7)	1400(855)	728(166)	5.9(1.0)	80(21)	140(19)
19	1399(667)	1977(657)	28(40)	30(40)	2.3 (1.5)	1.1 (1.9)	18.9(2.4)	54(23)	1778(764)	853(199)	5.7(0.8)	69(26)	121(23)
20	1667(772)	2539(1140)	24(30)	27(33)	1.1 (0.5)	1.2 (1.8)	20.0(1.9)	40(24)	1905(1466)	978(456)	5.6(0.9)	86(39)	132(42)
27A	1691(611)	2079(719)	76(90)	89(100)	1.1 (1.1)	0.7 (1.3)	19.8(5.3)	55(45)	1537(723)	1040(476)	6.4(1.1)	93(26)	121(27)
34	357(611)	2437(866)	38(46)	44(48)	1.1 (0.9)	1.4 (1.8)	18.4(3.0)	52(15)	1420(762)	848(221)	5.3(1.5)	37(40)	112(34)
46	1162(677)	2640(1115)	42(62)	59(80)	0.3 (0.2)	0.8 (0.5)	24.0(1.8)	69(19)	875(640)	846(1271)	5.7(0.7)	72(26)	125(19)
MEAN	1027*	2220	36	42	1.6	2.2	19.2	69	1617	1057	6.1	49	119*
MEAN	639**	1935	14	19	1.0	1.1	18.3	62	1435	990	5.9	39	115**

B. Barren Ultramafics

10	695(297)	1569(255)	14(8)	35(21)	2.6(1.1)	2.3(1.4)	18.0(2.5)	94(24)	3169(651)	1590(216)	8.5(1.0)	59(27)	155(17)
15	95(141)	1078(224)	51(57)	54(74)	3.9(0.9)	5.0(1.5)	13.2(0.6)	86(17)	2650(928)	1423(1126)	7.8(1.0)	11(10)	118(14)
30	208(70)	1215(148)	25(19)	31(20)	2.3(0.9)	3.1(1.3)	16.5(1.3)	49(19)	2461(272)	1353(457)	7.5(0.5)	24(6)	112(5)
31	327(113)	1587(145)	26(9)	32(9)	1.8(0.2)	2.3(0.6)	17.7(0.9)	43(11)	2221(693)	1289(213)	6.8(0.5)	33(6)	118(8)
32	350(219)	1514(445)	17(24)	22(26)	1.9(1.3)	2.7(1.7)	17.8(2.3)	45(22)	2314(851)	986(432)	6.3(2.0)	35(20)	112(17)
33	684(346)	1755(375)	10(9)	17(13)	2.3(0.8)	2.0(1.7)	18.4(2.5)	78(26)	3536(880)	1427(370)	7.5(0.7)	42(17)	133(11)
9	138(176)	1282(663)	23(30)	57(54)	3.1(1.9)	3.1(2.1)	13.8(4.6)	68(39)	1964(654)	1167(423)	6.8(1.6)	19(10)	110(20)
5	284(205)	1440(439)	27(22)	35(24)	2.3(0.9)	2.3(1.5)	15.4(3.4)	56(25)	1601(465)	1074(383)	6.8(1.8)	36(20)	124(33)
40	189(142)	1030(284)	41(42)	51(43)	2.9(0.9)	4.1(1.3)	14.3(2.3)	89(42)	2337(415)	1237(211)	7.5(0.7)	23(9)	124(12)
51	268(207)	1201(242)	38(43)	49(45)	3.3(0.9)	4.7(1.9)	15.2(2.1)	26(53)	2579(439)	1236(310)	7.2(1.2)	22(14)	120(14)
6	400(344)	1389(449)	36(53)	41(52)	2.0(1.1)	3.3(1.8)	14.1(2.7)	73(33)	2496(670)	1183(338)	8.3(1.7)	32(18)	118(15)
27B	463(256)	1525(489)	9(12)	17(23)	1.2(1.1)	1.7(2.3)	16.9(4.0)	54(24)	2675(1133)	1276(1002)	6.7(2.2)	35(19)	121(31)
27C	517(314)	1673(612)	14(35)	18(36)	1.0(0.3)	1.3(1.4)	19.1(3.3)	49(23)	2942(1042)	1089(532)	6.1(1.3)	44(24)	117(20)
36	480(356)	1593(564)	19(30)	31(40)	1.4(1.3)	1.7(2.0)	17.2(4.4)	65(25)	2683(1100)	1096(331)	7.3(1.7)	40(20)	125(20)
41	256(310)	1266(443)	57(50)	65(51)	3.8(1.0)	4.3(1.0)	13.8(2.1)	91(72)	2202(630)	1178(355)	7.7(0.9)	23(20)	109(11)
24	275(126)	1768(419)	19(22)	28(20)	2.0(0.6)	3.2(2.7)	16.3(3.5)	76(63)	2150(1008)	1228(473)	7.2(1.7)	24(16)	131(29)
8	698(306)	2272(421)	3(2)	12(1)	0.6(0.5)	0.6(1.0)	20.6(3.9)	42(15)	1914(1172)	752(308)	5.2(1.0)	27(13)	112(24)
21	454(198)	1564(571)	50(81)	52(84)	2.7(1.0)	3.6(1.6)	16.1(2.2)	86(36)	2350(531)	1262(262)	6.8(1.0)	29(13)	124(8)
28	567(461)	1737(675)	25(32)	33(36)	2.0(1.3)	2.4(2.2)	17.1(3.7)	66(70)	1793(849)	1131(371)	6.4(1.7)	44(21)	116(20)
35	434(203)	2110(587)	6(9)	9(9)	0.7(1.0)	0.7(1.8)	24.2(4.7)	42(18)	1581(636)	1030(384)	5.9(1.4)	21(11)	123(20)
38	856(575)	1561(622)	51(68)	52(65)	2.8(1.3)	3.3(1.8)	16.1(3.5)	73(28)	1926(678)	1052(279)	6.8(1.0)	44(25)	112(17)
39	733(427)	1936(676)	33(53)	38(55)	1.3(1.6)	1.6(2.1)	18.8(4.7)	47(27)	1293(572)	762(300)	4.8(1.6)	36(16)	112(12)
42	643(270)	2243(387)	15(13)	24(25)	1.2(0.7)	1.6(1.4)	18.5(2.3)	51(17)	1603(591)	1015(198)	6.4(0.9)	36(12)	122(12)
12	770(556)	1846(824)	25(29)	31(46)	2.0(2.4)	2.2(2.7)	17.7(6.0)	66(39)	1390(764)	1010(414)	6.1(1.0)	50(30)	117(24)
MEAN	429*	1530	29	39	2.2	2.8	16.4	76	2260	1128	7.0	32	119*
MEAN	270**	1388	13	22	1.6	1.5	15.9	65	2063	1054	6.7	26	117**

* ARITHMETIC
** GEOMETRIC

loss is variable so what does this mean ?

Table 3. Arithmetic means and standard deviations (in brackets) of most chemical determinations for groups of samples referred to in this study. Note that although there are differences between the means for Mineralized and Barren groups, standard deviations are such that a large number of results fall between the respective mean values.

Note that several areas designated Mineralized (including 13 Kambalda), have results which are similar to the mean values for all groups designated Barren. This is caused by sampling many individual komatiites in heterogeneous lava piles and is explained further in the text.

3.2 DISCRIMINANT ANALYSIS

Discriminant analysis is designed to answer the question. "What is the major component of variation that distinguishes between groups within a certain population?" It attempts to highlight the differences between known groups, when a number of variables are available, for a number of individuals within each group. In this particular instance, where there are thirteen variables for each individual, discriminant or canonical analysis can be best understood by imagining a plot of data points or samples in thirteen dimensional space, where each axis represents one chemical variable. The data form two swarms of points in the space, one of mineralized ultramafic samples and the other of barren ultramafic samples. The two swarms slightly overlap each other. Discriminant analysis can be used to determine linear combinations of the original variables, called canonical variates, such that the variation between the group means along the canonical axes defined by their linear combinations, is maximized. The first canonical variate is chosen, such that it is inclined in the direction of greatest variation between group means, relative to the dispersion of the observations within each group; the ratio of the between groups to within groups sums of squares for the first canonical variate is a maximum. The second variate is chosen such that it is uncorrelated within groups with the first variate and that the variation between group means, relative to the within group dispersion, is next greatest. Thus the population dispersion in the plane formed by the two canonical variates is maximized, and so on.

With two groups as in this study, the first canonical variate is usually the only one of significance. For two groups, if the canonical score D for any individual is such that D is greater than D_0, then the sample belongs to Group A, and D is less than D_0, the sample belongs to Group B. For example, the canonical score for any ultramafic sample in this study is derived from an equation such as:

$$D = C_1.Ni\underline{P} + C_2.Ni + C_3.Cu\underline{P} + C_4.Cu + C_5.Al + \ldots + C_{13}.Co$$

where C_1 to C_{13} are constants and $Ni\underline{P}$, Ni, etc. are the geochemical values expressed as logarithms. Canonical variates thus provide a measure of the distance between groups along axes providing maximized between group dispersion. Discriminate or canonical analysis programs assume that the variables are normally distributed; the groups have a common variance/covariance matrix; and the groups are in fact distinct. If these assumptions are violated, and in most cases geologic data is not homogenous, performance is adversely affected and a linear separating boundary may not adequately represent the structure of data. However, for this study it appears that the above assumptions are adequate.

Discriminant analysis was carried out at three stages using a progressively larger data base. In addition, two programs were used. Upper limits imposed on the variables to discard spurious samples were as follows: Ni 8000 ppm; CuP 350 ppm; Cu 350 ppm; Al 9 percent; Co 10 percent; Zn 350 ppm; Cr 5000 ppm; Mn 2800 ppm; Fe 15 percent; Co 300 ppm.

3.2.1 First and Second Stage Analyses

Discriminant analysis was first attempted using a program (Mulvar) from a Perth based service group (Geostatistics Pty.Ltd.) on a data base of 407 samples. Seventeen chemical and eight mineralogical variables were available for each sample. Several different analyses were attempted using various combinations of variables and groups of data. Initially, the data was divided into four groups: Major Mineralized; Minor Mineralized; Trough Wells and Barren; and analysis was attempted using all chemical variables. The results were encouraging but the distinction between Major Mineralized and Minor Mineralized areas was poor. A second analysis using three groups: Mineralized (100 samples), Trough Wells (145 samples) and Barren (162 samples)

was attempted and resulted in good discrimination. Trough Wells represents an area of Minor Mineralization but was included as a separate group to prevent bias in the mineralized group of samples. The data was divided into two sets; the discriminant functions were derived from the training set and then tested using the testing set. The percentage of samples classified correctly for each group are given below:

	PERCENTAGES OF SAMPLES CLASSIFIED AS:		
	Mineralized	Trough Wells	Barren
Mineralized group data	77-79	15-6	8-15
Trough Wells data	7-7	92-86	1-7
Barren group data	23-23	13-13	64-64

The first figure represents training set samples and the second figure testing set samples. Thus for the mineralized group training set data, 77 percent were correctly classified as Mineralized, 15 percent were classified within the Trough Wells group, and 8 percent were classified as Barren.

Several other data subdivisions were used in subsequent analyses and, in total, the results were considered encouraging enough to continue. In addition, after a study of the canonical functions it was decided that sulphur, selenium and vanadium could be excluded from future chemical analyses. The mineralogical variables proved to be of little discriminant value and petrologic examination of most samples was discontinued.

An enlarged set of data was then analyzed using the Biomed BMD07M discriminant analysis program. Samples were divided into two groups: Mineralized (728 samples) and Barren (683 samples). Fourteen chemical variables were available for each sample. Good discrimination was achieved and 80 percent of samples from barren areas and 82 percent of samples from mineralized areas were correctly classified.

3.2.2 Third Stage Analyses

Four discriminant analyses were undertaken using the Mulvar program (Geostatistics, Perth) with different data combinations. Three of these analyses, designated Analysis A, Analysis B and Analysis D will be discussed below.

In Analysis A, sixteen groups totaling 1320 samples were designated Mineralized and twenty-four groups totaling 1465 samples were designated Barren. The discriminant function A derived from this data base, classified 73.5% of Mineralized samples correctly and 79.3% of Barren samples correctly (Table 4). The major disadvantage with Analysis A was that it classified correctly only 33% of Kambalda samples, 47% of Windarra samples and 75% of Windarra South samples. Analysis B was undertaken in an attempt to increase the percentage of samples classified correctly. Samples assigned to the Mineralized category were limited to samples known to be within 70 m of significant sulphide mineralization. The discriminant function B derived from this revised data base improved classification significantly. 81.7% of Mineralized samples and 79.9% of Barren samples were classified correctly. Percentages correctly classified increased from 75 to 88 for Windarra South and 33 to 79 for Kambalda. Analysis A and Analysis B are highly correlated, but Analysis B is a more accurate function for discrimination.

In Analysis B, the geochemical results from overlying thin ultramafic lavas at Kambalda and Windarra South are excluded from the Mineralized group. It appears that this exclusion is valid and these lavas have a different "geochemical signature" to the underlying nickel sulphide host komatiites. Throughout this text, where discriminant analysis results are quoted without designation, they refer to Analysis B.

The Mineralized and Barren groups are separated in Analysis B by the following function:

$$D = -0.30\,(NiP) - 0.99\,(Ni) - 0.40\,(CuP) + 0.54\,(Cu) - 0.23\,(Al) = 0.10\,(Ca)$$
$$-0.70\,(Mg) - 0.91\,(Zn) + 1.32\,(Cr) + 0.09\,(Mn) - 0.67\,(Fe) - 0.36\,(CoP) + 1.92\,($$

Area Name	Map Code	DISCRIMINANT ANALYSIS A No. of Samples	DISCRIMINANT ANALYSIS A Percent Correctly Classified	DISCRIMINANT ANALYSIS B No. of Samples	DISCRIMINANT ANALYSIS B Percent Correctly Classified	RATIOS Ni/Cr	RATIOS Ni/NiP
A) Mineralized							
Forrestania	1	181	95	116	93	2.8	2.2
Windarra South	3	290	75	107	88	1.2	1.8
Windarra	7	57	47	34	53	0.9	1.9
Kambalda	13	132	33	33	79	0.7	3.2
Nepean	25	7	71	5	80	1.4	1.5
Scotia	26	7	100	7	100	3.0	1.4
Weebo Bore	50	22	100	22	100	2.7	1.1
Bouchers	2	274	85	116	89	1.6	3.3
Mt. Jewel	4	46	83	23	91	1.2	2.2
Trough Wells	11	141	50	93	51	0.7	2.2
Red Dam	16	9	89	9	89	1.9	1.2
Devines	19	16	81	16	81	1.1	1.4
Sir Samuel	20	9	67	9	67	1.3	1.5
Marvel Lock A	27A	43	75	43	84	1.4	1.2
Jubilee	34	22	82	22	50	1.7	6.8
Queen Victoria Rocks	46	62	94	62	100	3.0	2.3
B) Barren							
German Well	10	21	100	21	100	0.5	2.3
Yandel	15	11	91	11	100	0.4	11.3
Mt. Step	30	13	100	13	100	0.5	5.8
Lalor North	31	14	93	14	100	0.7	4.9
Collin Well	32	14	100	14	100	0.7	4.3
Dingo Range East	33	11	91	11	100	0.5	2.6
Red Well	9	100	99	100	99	0.7	9.3
Eureka	5	54	64	54	93	0.9	5.1
Airport	40	65	92	65	97	0.4	5.5
Yilmia Hill	51	246	83	120	89	0.5	4.5
Ennuin	6	129	83	129	90	0.6	3.5
Marvel Lock B	27B	107	87	107	89	0.6	3.3
Marvel Lock C	27C					0.6	3.2
Southern Cross	36	189	87	189	86	0.6	3.3
South Bulong	41	66	76	66	85	0.6	5.0
Mertondale	24	14	71	14	79	0.8	6.4
Mistake Ck.	8	43	77	43	70	1.2	3.3
Credo	21	12	58	12	67	0.7	3.4
Dingo Range West	28	73	56	73	62	1.0	3.1
Bullfinch	35	38	68	38	68	1.3	4.9
Mt. Jewel North	38	40	43	40	45	0.8	3.1
Heather Well	39	92	39	92	40	1.5	2.6
Yerilla	42	32	28	32	44	1.4	3.5
Area A	12	34	32	34	29	1.3	2.4
Mean, Mineralized		1318	73.5	717	81.7		
Mean, Barren		1457	79.3	1329	79.9		
TOTAL		2775	76.5	2046	80.5		

Table 4. Percent of samples correctly classified as either Mineralized or Barren by sample group, for Discriminant Analyses A and B. In Analysis B, 81.7 percent of samples originally designated Mineralized were similarly classified by Discriminant function B. Mean Ni/Cr and Ni/NiP ratios for each group are also shown. It is suggested in the text that for any group of samples to be Mineralized, the Ni/Cr ratio should exceed 1.0 and the Ni/NiP ratio should be less than 3.5. A number of groups such as Kambalda and Trough Wells do not conform to these guidelines and the reasons for nonconformity are discussed in the text.

Canonical score group means are 1.72 for the Mineralized group and 3.37 for the Barren group. Thus D_o is 2.55 and samples with a score of less than 2.55 are classified Mineralized and samples with a score greater than 2.55 are Barren. In practice, any samples which fall near to 2.55, either above or below, are of doubtful origin.

A "mineralization coefficient" is defined such that samples with scores between 2.55 and 2.13 have a low coefficient; samples between 2.13 and 1.72 have a moderate coefficient; samples between 1.72 and 1.30 have a high coefficient; and below 1.30 the coefficient is very high.

Averaged results such as those in Table 4 should be evaluated with caution, particularly if the samples cover a large geographic area, or a thick section of ultramafics. In volcanic suites such as Kambalda and Windarra South, the overlying komatiite lavas will give barren results whereas the underlying ore bearing komatiites have a high to very high coefficient of mineralization. This is not a problem in homogeneous, intrusive suites, which tend to yield reasonably consistent canonical scores throughout the intrusive.

In Table 4 within the Barren groups, several areas show poor correlation with the majority of Barren groups. Samples from Area A were classified as 29% Barren and 71% Mineralized; from Yerilla 44% were Barren and 56% Mineralized; from Heather Well 40% were Barren and 60% Mineralized; and from Mt. Jewell North 45% were Barren and 55% Mineralized. These areas which were originally designated as Barren because of no known association with nickel sulphides, may in fact be Mineralized. These areas are evaluated in detail in Chapter 7. Some evidence for Mineralization also occurs in the Southern Cross and Dingo Range West komatiites. Adequate evaluation of canonical scores requires some knowledge of the geology of the komatiite sequence.

In Analysis D, multiple discriminant analysis was undertaken, using all areas with more than 20 samples as separate populations. The object of this analysis was to provide an independent check on Analyses A and B and to determine

if areas or deposits could be grouped together, or whether regional differences could be defined. The resulting functions were applied to all groups and the results of this analysis are shown in Fig. 5 where mean canonical values for the first two canonical functions for each area are plotted. Groups above the dividing line on Fig. 5 can be regarded as Mineralized; and most of the groups below the line are Barren. This analysis is misleading to the extent that mean canonical scores for each group are plotted, and as has been shown above, in any volcanic komatiite suite there may be populations representative of both Mineralized and Barren komatiites. For example, point A on Fig. 5 represents mean scores of Lunnon and Durkin shoots at Kambalda whereas point 13 represents the mean of all Kambalda samples. D4 and D5 represent separate areas within the Southern Cross greenstone belt and 36 represents the mean of the Southern Cross group. Regardless of the difficulties in interpretation, discriminant Analysis D confirms that Mineralized and Barren komatiites can be separated. Analysis D also indicates that komatiites from different greenstone belts, or nickel provinces, may have distinct geochemical signatures. For example, the Southern Cross greenstone belt komatiites appear to be distinct from the Kalgoorlie-Norseman komatiites. The Wonganoo-Bandjawarn komatiites also form a distinct group and Area A, Yerilla and Jubilee have a similar geochemical signature. In the case of the Southern Cross greenstone belt, an exception is Trough Wells which plots within the Kalgoorlie-Norseman komatiites.

BUT WHAT IS DISCRIMINANT COMPOSITION FOR D ?

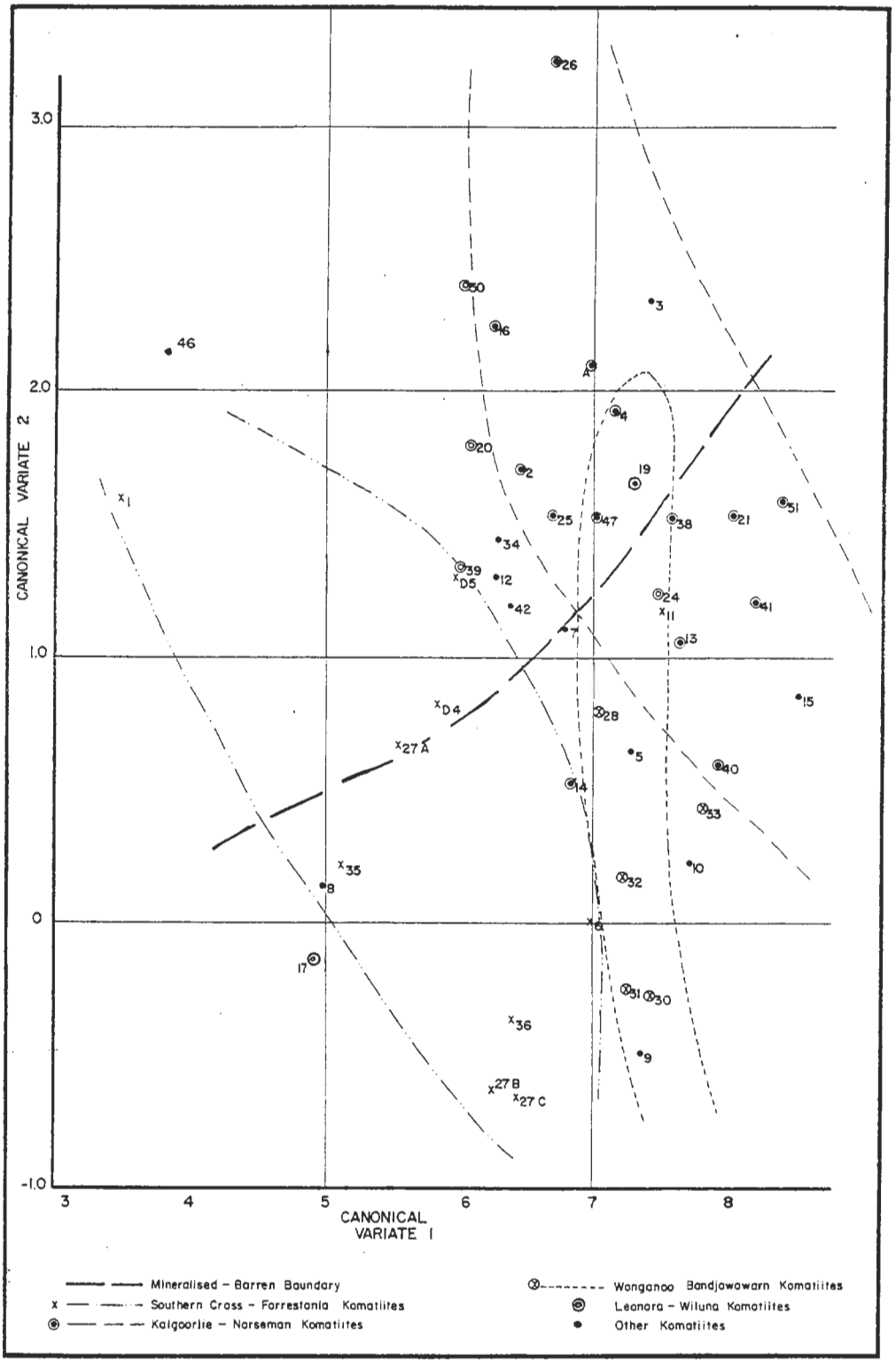

Fig. 5 . Plot of mean canonical scores for canonical variates 1 and 2, Discriminant Analysis D. Note the division between Mineralized and Barren groups and that groups of samples from different geographic regions fall within separate fields on the figure.

3.3 PRINCIPAL COMPONENT ANALYSIS

Principal component analysis differs from discriminant analysis in that it is concerned with major components of variation within the whole population, and is in no way oriented towards characteristics of known groups within the population. Principal component analysis provides a statistical method for disentangling and making sense of the variation in, and the correlations between, a number of variables. It provides linear combinations of variables, with maximum variability explained by the larger components - the first principal component coincides with the maximum variation, the second with the maximum of the remaining variations, etc. The coefficients which define the principal components may provide some insight into the nature of the interrelationship between variables, and into the underlying factors causing the variation. The first few components account for much of the information in the data and pirncipal components are effective in reducing the number of dimensions under study.

Principal component scores were computed for the first eight components for all samples included in the statistical analysis. The second component proved to be of value in detecting komatiite contacts in metamorphosed multiple sequences (see Windarra South). However, the conclusion drawn from the study of the principal component analysis is that in this instance, discriminant analysis is far superior in usefulness, not only in discriminating between Mineralized and Barren groups but also (by the use of individual canonical scores) in the interpretation of thick komatiite piles and in detecting regional geochemical differences.

3.4 CORRELATION ANALYSIS

A correlation matrix was computed separately for both Mineralized and Barren groups (Table 5) using logarithmically transformed data. The correlation coefficient "r" measures the degree of interrelationship between two variables. It is a unitless number ranging from +1 to -1. A correlation of +1 indicates a perfect direct relationship and of -1 a perfect inverse relationship. A coefficient of zero indicates the lack of any sort of linear relationship but not necessarily the lack of any relationship.

High correlations exist between the following pairs of variables in both mineralized and unmineralized groups. The numbers listed after each pair of variables are the coefficients for the Mineralized and Barren groups respectively. High positive correlations include:

CuP and Cu	(.96, .89)
NiP and CoP	(.84, .81)
NiP and Ni	(.75, .66)
Ni and Mg	(.63, .51)
Ca and Mn	(.53, .53)

High negative correlations include:

Al and Mg	(-.60, -.64)
Ni and Al	(-.46, -.63)

The following groups of variables have strong interrelationships:

Ni, NiP, Mg, CoP, Co, Al and Ca; Al, Ca, Zn, Mn, Fe and Mg.

These relationships reflect the normal variations throughout the komatiite suite; and, in general, as Ni, NiP, Mg, CoP and Co increase, Al, Cu, Zn, Mn and Fe decrease. The strong positive correlations between Ni-Mg and negative correlations between Al-Mg and Ni-Al, indicate that the nickel content of any komatiite increases with Mg whereas with increasing Al both Mg and Ni decrease. These changes are fundamental to the komatiite series.

BUT APE WELL KNOWN & DONT NEED COR. ANALYSIS TO SHOW

CORRELATION MATRIX MINERALIZED AND BARREN ULTRAMAFICS

	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co	
NiP		.66	-.05	-.14	-.50	-.32	.51	-.25	-.03	-.19	-.26	.81	.35	N
Ni	.75		-.32	-.37	-.63	-.51	.80	-.46	.11	-.39	-.37	.43	.43	N
CuP	.41	.20		.89	.53	.50	-.39	.45	.05	.36	.37	.12	.03	C
Cu	.41	.22	.96		.55	.52	-.47	.46	.02	.37	.39	.04	-.02	C
Al	-.28	-.46	.15	.10		.70	-.64	.61	.18	.47	.55	-.29	-.14	A
Ca	-.32	-.44	.05	.03	.44		-.54	.46	.10	.53	.37	-.17	-.18	C
Mg	.37	.63	-.22	-.19	-.60	-.45		-.47	.16	-.29	-.36	.29	.40	M
Zn	-.10	-.20	.25	.22	.33	.32	-.35		.24	.51	.58	-.14	.10	Z
Cr	-.05	.02	.19	.12	.54	.18	-.20	.24		.20	.38	.04	.36	C
Mn	-.14	-.22	.11	.07	.34	.53	-.24	.47	.24		.54	0	.16	M
Fe	-.007	.04	.19	.15	.21	.17	-.02	.25	.41	.42		-.05	.37	F
CoP	.84	.54	.46	.45	-.14	-.17	.20	-.02	.15	-.04	-.10		.42	C
Co	.41	.54	.29	.29	-.03	-.12	.26	.06	.30	.15	.51	.52		C
	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co	

Barren

Mineralized

Table 5. Correlation Matrices computed from the mean values of all groups designated either Mineralized or Barren. Two general observations should be noted: (1) Most correlations are much stronger in the Barren than in the Mineralized ultramafics; (2) the chalcophile elements, Cu, Ni, Co and Fe (constituents of nickel sulphide deposits), in particular, show moderate to strong correlations with the rock forming elements, Mg, Mn, Ca, Al in Barren ultramafics but only weak or no correlation in the Mineralized ultramafics. In addition copper has quite different relationships in both groups (see text).

Some relationships are restricted to, or emphasized within, either Mineralized or Barren groups. The Mineralized group shows a strong relationship between the following groups of elements: NiP, CuP and Cu; CuP, CoP and Co; Al and Cr. Thus the Mineralized group emphasizes relationships between the partial or sulphide extractions, which suggests a higher sulphur content for this group than the Barren ultramafics. The Barren group emphasizes the following interrelationships: Cu, Al, Ca, Mn, Fe and Mg; Ni and Fe; CuP, Al and Ca.

Two general observations should be noted:

1. Most correlations are much stronger in the Barren than in the Mineralized ultramafics;
2. The chalcophile elements, Cu, Ni, Co and Fe (constituents of nickel sulphide deposits), in particular, show moderate to strong correlations with the rock forming elements, Mg, Mn, Ca and Al in Barren ultramafics, but only weak or no correlation in the Mineralized ultramafics.

Copper is outstanding in its behaviour in that it has moderate positive correlation with Fe, Mn, Ca and Al and negative correlation with Mg in Barren ultramafics but shows no correlation with these same elements in Mineralized ultramafics. In addition, Cu shows moderate positive correlation with Ni, NiP, Co and CoP in Barren ultramafics. Copper in Barren ultramafics increases as the magnesium and nickel content decreases, that is, in the less ultramafic units. However, in Mineralized ultramafics there is only a slight tendency for Cu to increase with a decrease in Mg, and with decreasing Ni it also tends to decrease (and vice versa). These correlation differences suggest that most of the Ni, Cu and Co, and some of the Fe in Mineralized ultramafics is held as a sulphide fraction, not related to the rock forming minerals. An alternative or complementary explanation is that a part of this sulphide phase has been concentrated and removed in an immiscible sulphide-oxide melt.

Whereas Ni has low to moderate correlation with Cu and Co in Mineralized ultramafics, it shows no correlation with Fe. In Barren ultramafics, Ni has a weak to moderate negative relationship with Fe. By contrast, Fe is moderately correlated with cobalt in both groups. Other relationships which should be noted include a low negative correlation between Cr and Mg in Mineralized ultramafics, in contrast to a low positive correlation in Barren ultramafics; a much stronger relationship between Cr and Al in Mineralized ultramafics than Barren; and the relatively strong correlations between Zn and Fe; Mg, Ca, Al, Cu, CuP, Ni and NiP in Barren ultramafics compared to much weaker correlations in Mineralized ultramafics.

The highly chalcophile nature of copper is confirmed by the high correlation coefficients between Cu and CuP for both Mineralized (0.96) and Barren (0.89) ultramafics. Most of the copper in all komatiites is present as CuP which is presumably copper sulphide. In Mineralized komatiites 41.2% and 46.3% of Co and Ni respectively is present as sulphide whereas in Barren komatiites 26.9% and 18.0% is present as sulphide. Nickel is slightly more chalcophile than Co but the difference is slight. This relationship is confirmed by the correlation coefficients of 0.75 and 0.52 for NiP-Ni and CoP-Co respectively.

Nickel and cobalt have a correlation coefficient of 0.43 in the Barren ultramafics and 0.54 in the Mineralized ultramafics. Cobalt however does not always closely follow Ni in its distribution. Whereas Ni values differ between cumulate and silicate liquid portions of thick and thin units, Co remains relatively constant throughout. Mean values for Ni between thick and thin units in Mineralized ultramafics also differ substantially but differences in Co content are very small. The correlation coefficient of approximately 0.5 between Ni and Co indicates some interdependence and individual small fluctuations in Ni content within individual komatiite units is sometimes accompanied by complimentary changes in Co. High Co in an otherwise chemically average unit tends to indicate the unit is Barren.

Ca and Mg have correlation coefficients of -.45 in Mineralized komatiites and -.54 in Barren komatiites. A much stronger negative correlation is indicated in some instances, particularly Forrestania hole 5 (Fig. 43), some of the Boucher holes, crosscut A Kambalda, Yilmia, etc., where sharp increases in Ca content in the middle of a high Mg section have a corresponding decrease in Mg. These differences would appear to reflect addition of Ca and removal of Mg during carbonate alteration. Highly carbonate altered rocks also tend to be depleted in NiP and CoP and in some instances Ni. These changes add a further risk to interpretation of geochemical data without knowledge of the mineralogy of the samples in question.

Barrett et al. (1977) list correlation coefficients for Se, Fe, Co, Ni, Cu and Zn for volcanic type Fe-Ni sulphide ores. Most of their coefficients are remarkably similar to those of the mineralized ultramafics, except for Fe-Ni and Fe-Co which are 0.53 and 0.02 respectively compared to 0.04 and 0.25 respectively in the mineralized ultramafics. The fact that coefficients between the metals Co, Ni, Cu and Zn are similar in both sulphide concentrations and ultramafic host suggest that these metals have not been added to the system in significant quantities after the formation of the komatiite magma. The different relationships between Fe-Ni and Fe-Co in sulphides and ultramafic suggest that Fe has been added to the sulphide system from an external source and not derived entirely from the ultramafic.

3.5 RELATIVE IMPORTANCE OF EACH VARIABLE

It has already been pointed out that no single variable differentiates between Mineralized and Barren groups, although in total the thirteen variables discriminate accurately. An estimation of the most important elements can be obtained from a study of the canonical function. A relatively high value constant for a particular element indicates that the element or variable is significant in the discriminating or canonical function. Thus Co, Cr, Ni, Zn and Mg appear to be most important. Mn and Ca have no effect on the function. However, this approach considerably over-simplifies the problem and does not take into account the normal range of chemical values for each variable or whether certain variables are highly correlated and tend to cancel each other out.

To assess the relative discriminant power of each variable, graphical plots of partial canonical score against geochemical value for the normal range of values for that variable in komatiites were constructed (Figs. 6-9). In both Analyses A and B, a decrease in canonical score moves that sample towards the Mineralized group. Most plots are curves (as expected with a log function) and thus the discrimination power of most variables changes with the absolute geochemical value of the variable. For example, in Fig. 7 it can be seen that for copper, a small change in value in the range 2 to 20 ppm has a very large effect on canonical score, but increases in Cu values above 60 ppm have a relatively small influence on canonical score. Thus the slope of each graphical plot, at any point, can be regarded as a measure of the discrimination power of that variable, at that particular chemical value.

The variables which have greatest discrimination power throughout the relevant geochemical range for this study are: Ni, Cr, Zn and Co. Copper and CuP have significant power in their lower geochemical ranges. NiP is significant for Analysis B only. Mg and Fe have low discriminate power and

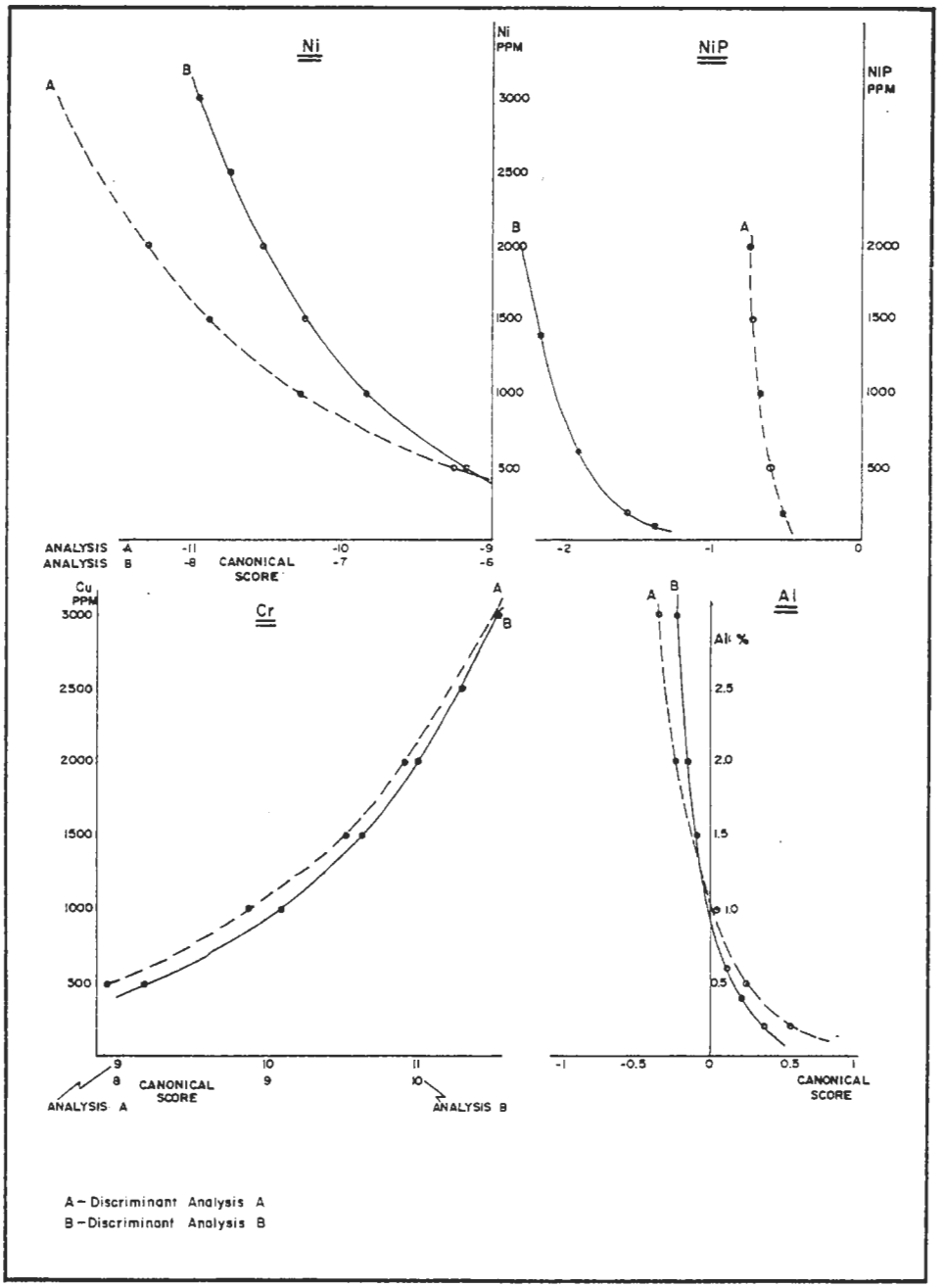

Fig. 6. Plots of partial canonical scores for Ni, NiP, Cr and Al versus geochemical value for the range of values common in komatiite rocks.

CoP, Al and Mn have low discriminant power in certain parts of their geochemical ranges. Calcium has no influence on either function. Discriminant Analysis B, because of its better classification record, is the more useful of the two functions and further comments will be restricted to this analysis.

The canonical means for the Mineralized and Barren groups are 1.72 and 3.37 respectively. Thus, individual samples with canonical scores of less than 2.55 are regarded as Mineralized, and those with scores greater than 2.55 are Barren. In practice, if a sample has a score of between 2.13 and 2.92, it should be evaluated carefully. If it belongs to a group of samples from the same komatiite sequence which has a mean canonical score of less than 2.13, the sample can be regarded as Mineralized. The reverse is true if the group has mainly canonical scores greater than 2.92.

A change of only 0.8 is needed to move a sample's score from the mean of the Mineralized group to the boundary between the two groups (Do). This would result if the Ni value is reduced from 2500 ppm to 1100 ppm (assuming all other variables to remain constant (Fig. 6); or the NiP value from 2000 ppm to 150 ppm; by an increase in the Cr from 1000 ppm to 1750 ppm; by increasing Cu from 5 ppm to 21 ppm etc. However, as was shown in the correlation analysis, most of these variables are interrelated and it is thus unrealistic to consider them separately. Nickel and NiP have a strong positive correlation and thus when Ni decreases, NiP can be expected to decrease also. Thus Ni and NiP have a cumulative effect on the canonical score. Copper and CuP are also highly positively correlated. However, an increase in the Cu value increases the canonical score, whereas an increase in CuP value decreases the canonical score. The cumulative effect of Cu and CuP is illustrated in Fig. 7. To derive this graph, it was assumed that the CuP to Cu ratio is constant at 0.88. Thus, after CuP is taken into account, a change from 5 ppm Cu to 21 ppm Cu would increase a canonical score by only 0.1. However, with Ni, if it is assumed Ni and NiP are highly correlated, a decrease in Ni from 2500 ppm to

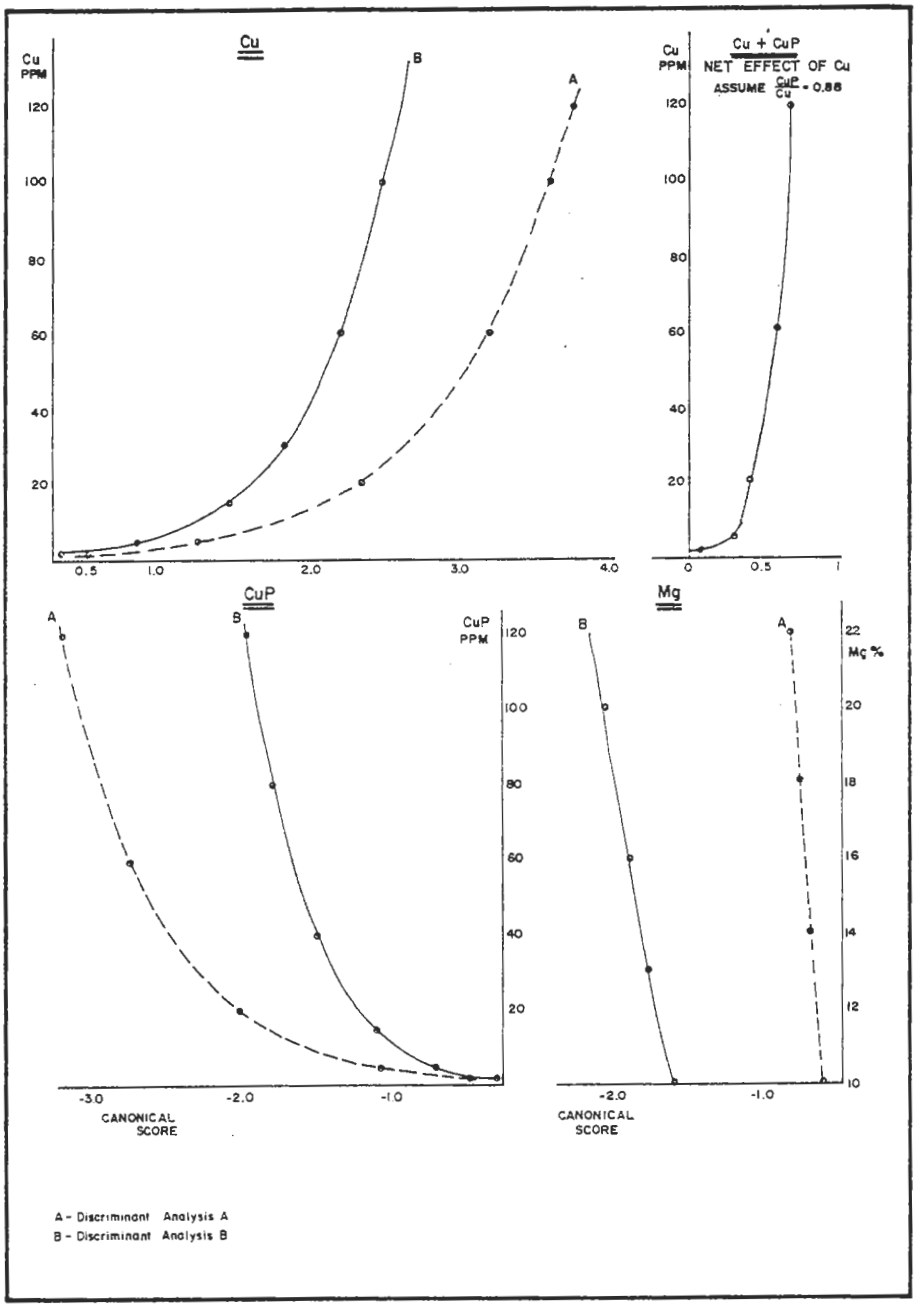

Fig. 7. Plots of partial canonical scores for Cu, CuP and Mg versus geochemical values for the range of values common in komatiite rocks. A plot of the "net effect" of Cu for Cu values in the range 0 to 120 ppm, versus partial canonical score is also included and is derived from the Cu and CuP plots assuming a constant CuP to Cu ratio of 0.88. Note that although both Cu and CuP individually have a significant influence on canonical score, the net effect plot indicates that Cu is only significant below 20 ppm.

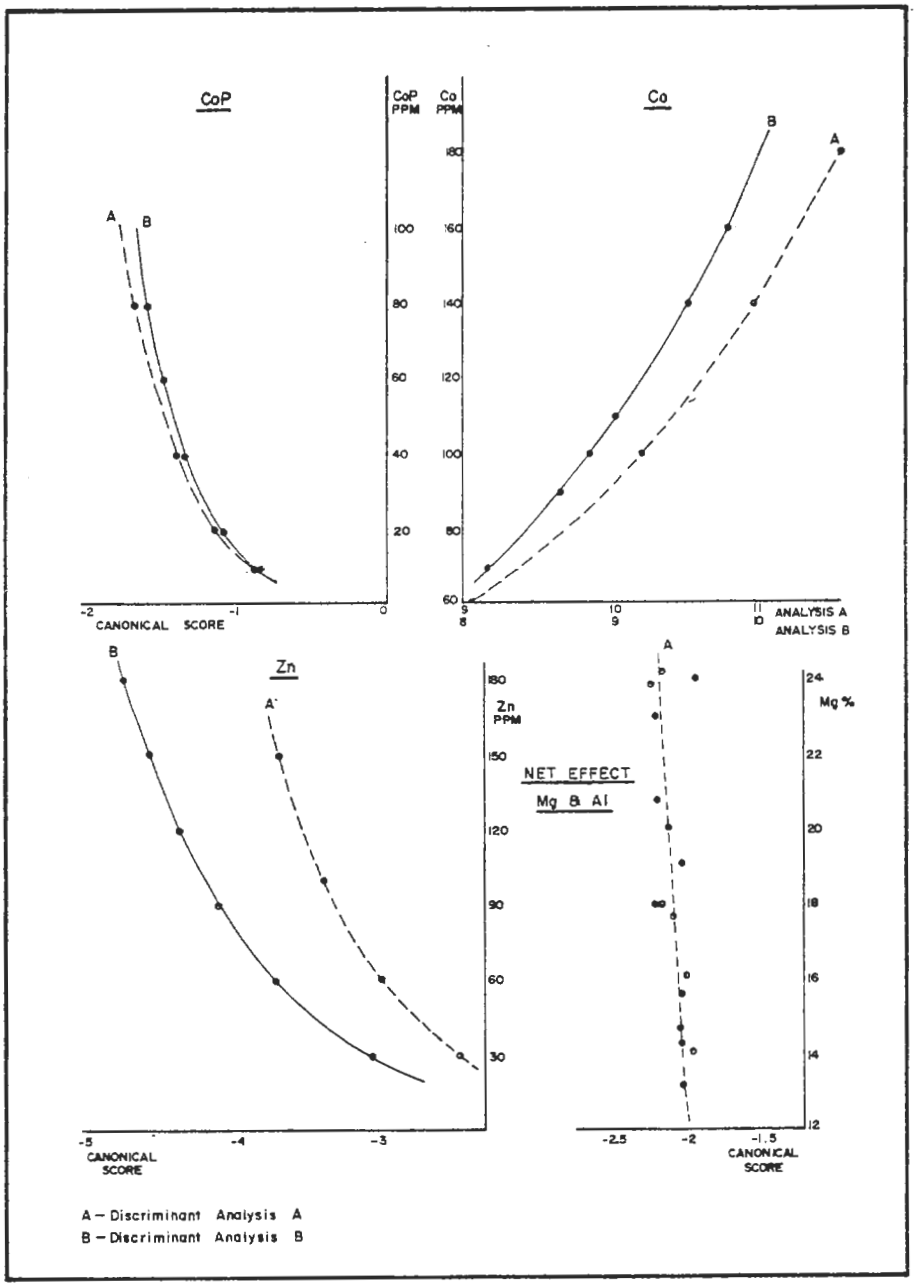

Fig. 8. Plots of partial canonical scores for CoP, Co, and Zn versus geochemical values for the range of values common in komatiite rocks. The lower right plot shows partial canonical scores for Mg plus Al versus Mg values in the range 12 to 24 percent. The Mg and Al values are mean values for representative sample groups and are derived from Table .

1500 ppm could reasonably be expected to result in a decrease of NiP from say 1000 ppm to 400 ppm. The result is an increase in canonical score from the mean of the Mineralized group 1.7 to 2.5, or the dividing point (Do) between the Mineralized and Barren groups.

In Fig. 8, lower right, canonical scores were computed for mean Mg and Al values for 16 groups (from Table 3) and plotted against mean Mg values. The resultant graph suggests that combined Mg and Al do not contribute greatly to the discriminant function but that in general, an increase in Mg tends to move any sample towards the Mineralized group. Some of the earlier discriminant analysis functions placed more emphasis on NiP, Fe and Mg and far less emphasis on Co. To a large extent this is probably caused by the fact that there is a high degree of correlation between certain variables, and the discriminant analysis programs, not requiring the same information twice, reject or downgrade one of the variables. However, it is worth noting that all functions have emphasized the importance of Ni, Cr, Zn and to a lesser extent NiP, CoP, Cu and Mg. Although it has not been attempted, it is probable that a high degree of discrimination could be achieved using the above six variables only. WHAT 6 ? LOOKS LIKE 7 TO ME BUT DOESN'T SEEM TO BE MUCH DIFFERENCE IN Zn Sc CHART 4

From the preceding discussion and a visual study of the chemical data it was concluded that the ratios Ni/NiP and Ni/Cr were important in separating Mineralized from Barren samples. These ratios for each area are listed in Table 4. (P37) In general it is considered that high Ni/Cr and low Ni/NiP ratios are indicative of mineralized ultramafics. Any group of samples with both a Ni/Cr ratio greater than 1 and a Ni/NiP ratio of less than 3.5 has a high probability of being Mineralized. The Ni/Mg ratio is also significant and a ratio of less than 80 suggests these samples are Barren. The higher the ratio the more probable it is that they are Mineralized. SOLP. A FUNC. IN OF SULFIDE - NICKEL

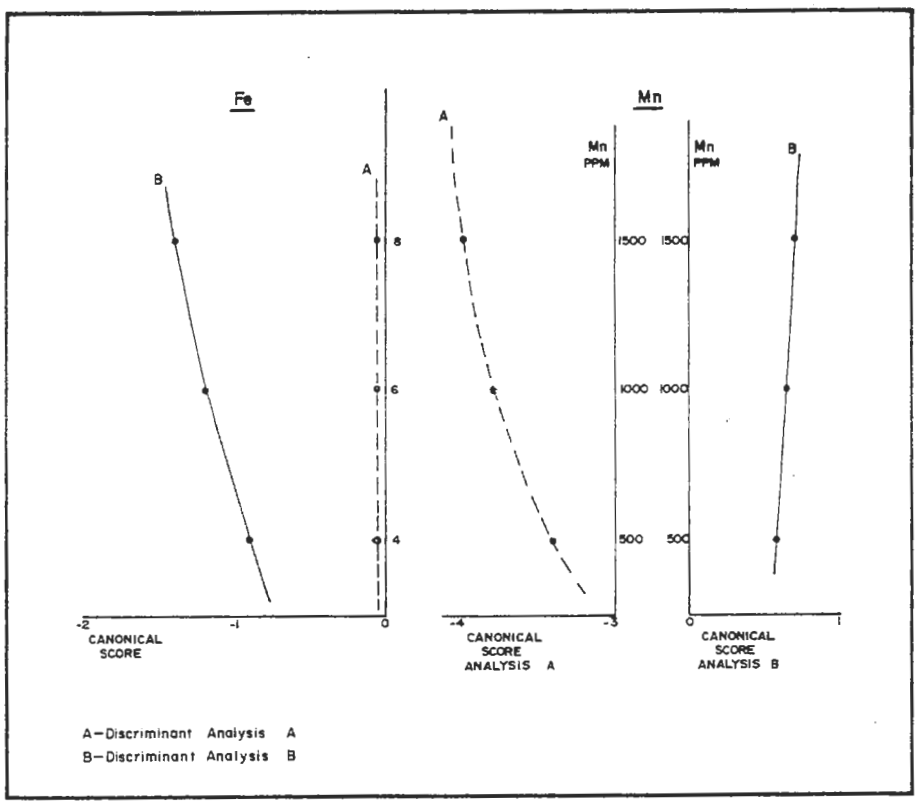

Fig. 9 . Plot of partial canonical scores for Fe and Mn versus geochemical values for the range of values common in komatiite rocks.

Groups of samples in which only one ratio is favorable may or may not be Mineralized. In these cases, it is often possible to break the samples into sub-groups based on geology. For example, at Kambalda (described in Chapter 4) the samples can be subdivided into three subgroups: Lunnon Shoot, Durkin Shoot and overlying komatiite lavas (thin units). Whereas the combined Kambalda samples have an Ni/Cr ratio of 0.7 and Ni/NiP ratio of 3.2, Lunnon Shoot samples (thick units) are 1.65 and 2.04 respectively; Durkin Shoot samples (thick units) are 1.66 and 1.43 respectively; and the overlying komatiite lavas (thin units) are 5.37 and 0.56 respectively.

IN FACT THE THIN UNITS TEND TO BE MOST FAVORABLE!

CHAPTER 4

4. CHEMICAL CHARACTERISTICS OF VOLCANIC AND INTRUSIVE KOMATIITES

Mean chemical values for West Australian komatiites are as follows:

	NiS	Ni	CuS	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoS	Co
Mineralized	1027	2220	36	42	1.6	2.2	19.2	69	1617	1057	6.1	49	119
Barren	429	1530	29	39	2.2	2.8	16.4	76	2260	1128	7.0	32	119
All Samples	725	1870	32	40	1.9	2.5	17.8	72	1930	1090	6.5	40	119

As is shown in Table 2 these values agree with values published for West Australian komatiites by Naldrett and Turner (1977) except that mean Mn values in this study are substantially less than those quoted by Naldrett and Turner.

Komatiites in Western Australia have been divided into two separate and distinct suites or sequences - volcanic and intrusive. These suites can be distinguished on the basis of external and internal geologic form and habit; geochemistry and characteristics of related sulphide mineralization.

Metamorphism, serpentinisation and talc-carbonate alteration have altered many komatiites to the extent that it is often not possible to determine visually or petrographically to which suite a particular sample belongs. However, they can usually be classified using chemical data.

As a general rule, chlorite and amphibole rich komatiites are not mineralized and indicate a sequence of volcanic komatiite lavas. However, care must be taken in interpretation if only a few samples are available as a chlorite amphibole section of komatiite could represent the uppermost portion of a mineralized thick unit (see Section 4.1).

4.1 VOLCANIC KOMATIITE SUITE

The volcanic suite is the predominant komatiite association in Western Australia. It most commonly occurs as thick heterogenous ultramafic lava piles which contain two principal types of ultramafic units.

The basal section of the pile consists of a relatively small number of thick units, mainly fine to medium grained olivine cumulate rocks of peridotite, olivine peridotite or rarely dunite composition. These units may be partly differentiated with thin pyroxene peridotite or pyroxenite upper sections. Spinifex texture may or may not be present. They have been considered by most authors to be sills, emplaced essentially contemporaneously as subhorizontal bodies in a lava pile. Alternatively they may represent thick lava flows extruded at the onset of komatiite volcanism.

Overlying the thick units and forming the bulk of komatiite in the pile, are multiple thin units. These units are well differentiated with thin olivine cumulate lower sections of peridotite or pyroxene peridotite composition and relatively thicker upper sections of pyroxene peridotite or pyroxenite composition. Spinifex texture is characteristic of unaltered units. The thin units are regarded as ultramafic lavas. The final phase of komatiite volcanism in some areas was the extrusion of varying thicknesses of thin high Mg basalt lavas.

Barnes et al. (1974) subjected a thin unit flow, 1.24 m thick, to a detailed petrographic and chemical scrutiny. The flow as described by Barnes consisted of the following zones (Fig. 10):

A1 - Chilled and fractured flowtop

A2 - Fine-grained, spinifex textured pyroxene peridotite

A3 - Spinifex textured pyroxene peridotite

B1 - Foliated olivine peridotite

B2 - Porphyritic olivine peridotite

B3 - Lower chilled zone

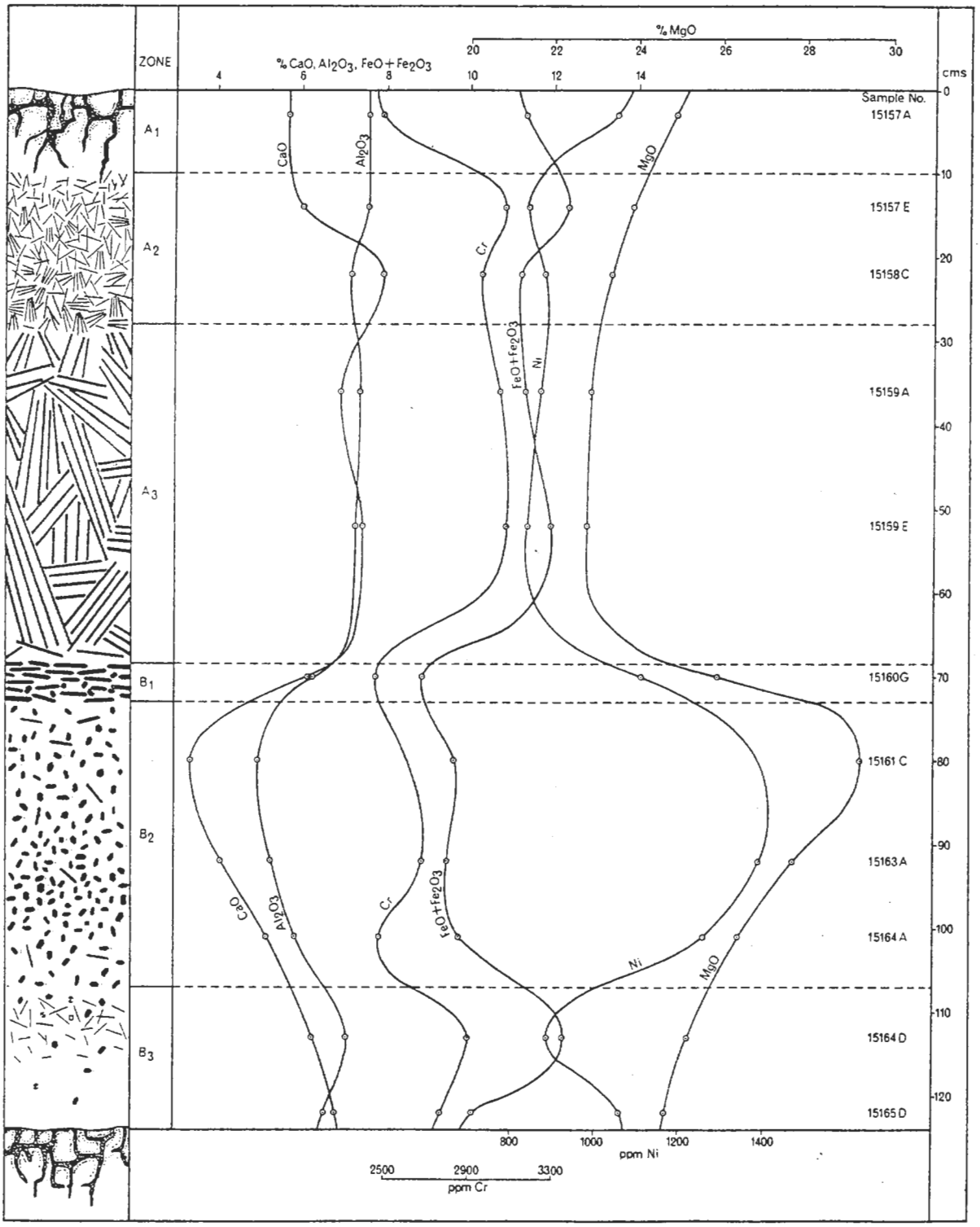

Fig.10. Chemical variation within a single komatiite lava from Mt. Clifford (reproduced from Barnes et al. 1974).

The A1 zone is divided into two sections. The upper section has an agglomeratic appearance and consists of either patches of devitrified glass containing 14% small euhedral olivine phenocrysts, or of small matted plates of olivine up to 0.4 mm long. The lower section grades into the spinifex zone below. The A2 zone is characterized by dendritic chromite and feathery clinopyroxene as interstitial material between "spinifex" blades of olivine. The A3 zone contains large books and fans of olivine plates. Model analyses of this zone indicate the rock is 40% bladed olivine and 60% interstitial material. Zone B1 is narrow and characterized by elongate skeletal olivine plates in sub-parallel orientation. Interstitial material is acicular clinopyroxene and dendritic chromite. In addition, euhedral olivine crystals increase in abundance with depth. The B2 zone consists of 55% euhedral olivine and 5% platy olivine, in a matrix of fine-grained feathery clinopyroxene and rare euhedral chromite. Zone B2, which is the lower chilled zone, is similar to Zone A1. Chromite is present throughout the chilled zone as small dendritic crystals, but in the lowermost glassy portions it occurs only as a fine dusting of minute grains. Note that nickel, sulphur and magnesia are concentrated in the olivine peridotite whereas chromium, titanium and iron are concentrated in the spinifex zone. Nickel in general follows the magnesia curve, indicating that in these low sulphur komatiites the partitioning of nickel between a sulphide phase and the olivine lattice is in equilibrium. A similar equilibrium exists between chromium in chromite and in the clinopyroxene lattice.

Within a typical volcanic komatiite pile Ni, Mg, Ni$\underline{P}$ and Co$\underline{P}$ tend to increase and Cr, Al and Cu tend to decrease towards the base. Cobalt remains constant. Zn, Mn and Fe are erratic but in some instances Zn shows an increase and Mn and Fe decrease towards the base of the sequence. These overall trends are severely modified by strong trends within individual komatiites.

Complete geochemical profiles through thick units at Kambalda, Bouchers and Windarra South show that values for Ni, NiP, Mg and CoP consistently increase and Cr decreases toward the base of each unit. Magnesium often has a maximum value in the center or just below the center of the unit. The changes in Ni and Mg reflect the gradation in rock type from spinifex textured pyroxene peridotite at the top to equant olivine textured peridotite or olivine peridotite in the lower part of the unit. A thin (0.25 m) pyroxenitic, chilled contact zone may be present at the base.

The mineralization coefficient of a thick unit must be determined from the olivine cumulate section of the komatiite (lower two-thirds to seven-eights of the unit). The pyroxenitic or pyroxene peridotite, silicate liquid derived upper portion (as distinct from the lower olivine cumulate section) which may vary from 1 to 10 m in thickness, will always show a lower mineralization coefficient than the cumulate section (due to higher Cr and lower Ni content) and in some cases may indicate the unit is Barren. Chemical values for the cumulate section of a thick unit with a moderate to high mineralization coefficient are of the order of: NiP 1000 ppm; Ni 2100 ppm; Cu and CuP 30 to 90 ppm; Al 1 to 2%; Ca 0.1 to 3%; Mg 17 to 24%; Zn 60 ppm; Mn 1000 ppm; Cr 1300 ppm; Fe 5.5%; CoP 55 ppm and Co 120 ppm. In general, if Nip or Ni are less than 500 and 1800 ppm respectively or Cr greater than 2100 ppm, the unit can be regarded as Barren. With higher Ni, Cr can also rise and the unit still be classified as Mineralized. As was pointed out earlier the Ni to Cr ratio should always exceed one.

Thick units range up to 60 m in width, but average width is probably of the order of 25 m. With widths of less than 15 m, the Mg content of both the cumulate sections and the unit as a whole,decreases. There is very little data available as to the lateral extent of thick units but some at least extend for several thousand meters. At Scotia the ore host thick unit is a maximum of 50 m thick, extends for 500 m along strike and to an unknown depth.

Examples of probable thick units in volcanic associations which are Barren are as follows: Wongi South - Mg up to 20% but has low Ni (1300 to 1600 ppm) and high Cr (2500 to 3000 ppm); Yilmia - Mg 18.1 to 20.4%, Ni 2350 ppm, NiP 50 ppm, Cr 700 ppm. In this last example although Ni, Cr and Mg are all favorable, the NiP value of only 50 ppm indicates very little sulphur in the komatiite.

The Katiniq Sill in Ungava, Quebec (Wilson et al. 1969) shows some similarities to a thick unit within a volcanic sequence. The sill consists of an upper, lower magnesia rich section (20 m thick) of pyroxene peridotite, underlain by a zone of peridotite and olivine peridotite (70 m thick), which in turn is underlain by a thin (8 m thick) basal pyroxene peridotite or chilled contact zone. Magnesia is a maximum approximately 70 m below the top of the sill. Cobalt, Cu and Zn have similar values to Western Australian thick units, but Ni and S are considerably higher. Chromium is not reported (Wilson et al 1969 - Table 2). Overlying the sill are moderate magnesia rocks (MgO - 20%) named basalt by Wilson et al. 1969, which are pyroxenitic in composition and are probably equivalent to thin unit komatiites.

Nickel sulphide deposits in volcanic suite komatiites vary from very small (a few tonnes) to moderate in size. For example, individual shoots at Kambalda are seldom larger than 3 to 4 million tonnes but total ore reserves at Kambalda are of the order of 20 million tonnes at plus three percent (+3%) Ni and total mineralization present is probably two to three times that figure.

The deposits occur as disseminated and massive-sulphide accumulations at or near the basal interface of ultramafics with other rocks, or less commonly at internal ultramafic contacts. Wall rocks may be mafic volcanics, sulphide-rich shale, sulphide-facies banded-iron formation or metasediments of various types.

Primary sulphides consist of pyrrhotite and pentlandite with less common pyrite and chalcopyrite. Millerite is significant in some deposits, and violarite is important in zones of oxidation and secondary enrichment. At Nepean (Sheppy and Rowe 1975), the massive ore is 60% pentlandite, 20% pyrite, 18% pyrrhotite, with minor chalcopyrite, cubanite, mackinawite and valeriite. The ore averages 1.5 m in thickness and has a Ni:Cu ratio of 15:1 and an Ni:Co ratio of 60:1. At the Lunnon Shoot, Kambalda (Ross and Hopkins 1975), the mineralization consists of one-meter thick massive sulphides overlain by 2m of disseminated sulphides. Pyrrhotite is the predominant sulphide with lesser amounts of pentlandite and chalcopyrite. Pyrrhotite-pentlandite ratios vary from 0.8:1 to 2.3:1. Average Ni:Cu and Ni:Co ratios are 13:1 and 54:1 respectively. Many occurrences appear to have some degree of primary or secondary structural control. Embayments or depressions in the footwall komatiite contact, thickenings in the komatiite and some types of folding may be important in localization of sulphides. Sulphide-bearing sediments (black shales) may be spatially related to nickel-sulphide mineralization, in that these sediments may occur along strike in similar stratigraphic positions to the nickel sulphides. Sulphide sediment immediately adjacent to nickel sulphide is uncommon.

The geochemistry of several mineralized and barren volcanic suites will be described below. Others will be discussed in later sections of this thesis. The description of Windarra South illustrates how geochemistry can be used to interpret metamorphosed, apparently structurless, complex komatiite sequences.

4.1.1 Kambalda

Kambalda is approximately 40 miles south of Kalgoorlie (Fig. 58). The geology has been described in detail by Woodall and Travis (1969) and Ross and Hopkins (1975). There are eleven known separate areas of nickel sulphide mineralization within komatiite ultramafic hosts in an area 12 by 6 km (Fig. 11).

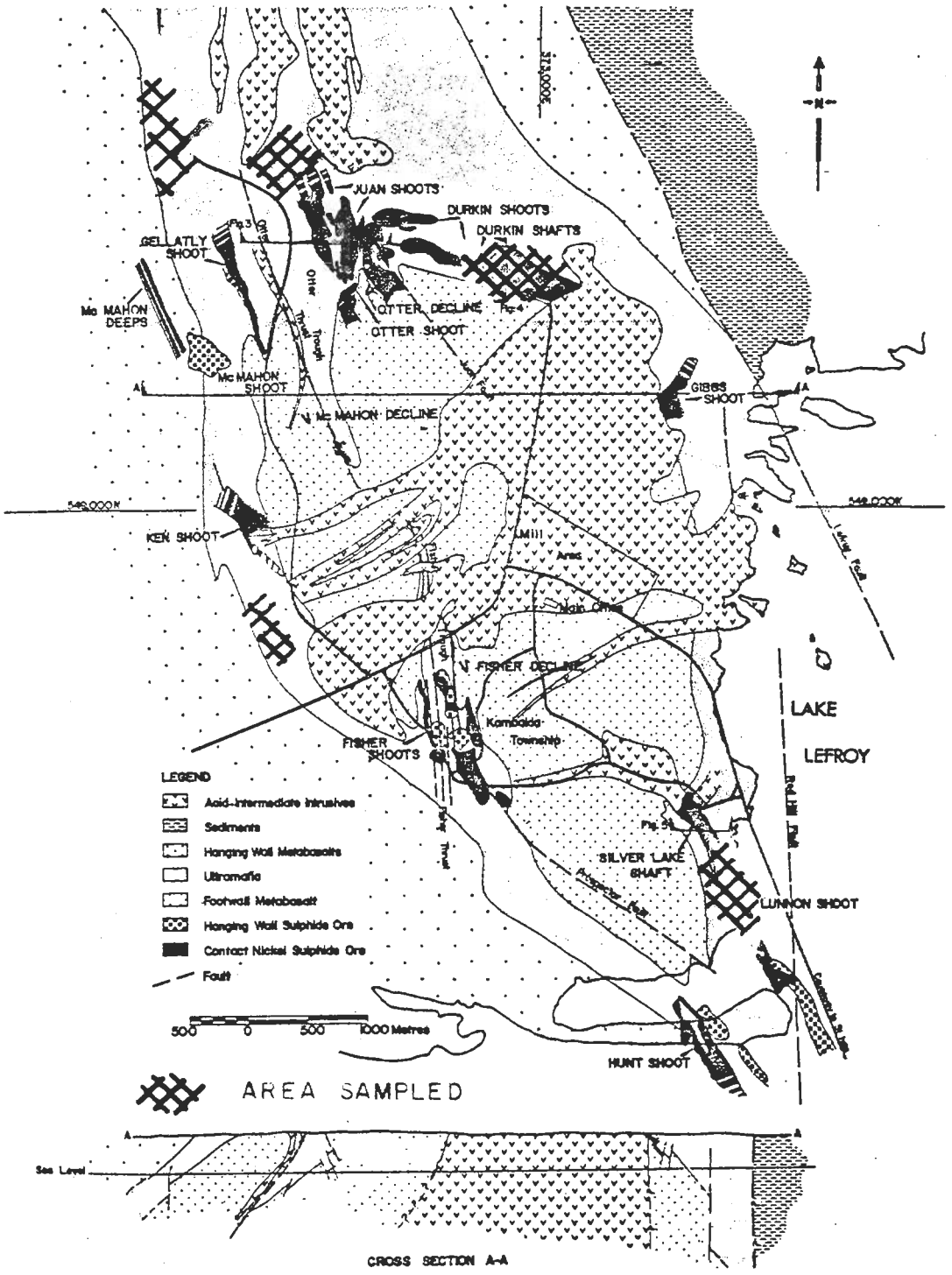

Fig. 11. Geological plan of Kambalda dome (after Ross & Hopkins, 1975) showing relationship of areas sampled to nickel orebodies.

A komatiite sequence which ranges in thickness from 240 m to more than 600 m forms a domal feature and surrounds a core of fine-grained, pillowed metabasalts. The dome plunges to the north-northwest and south-southeast at 20 degrees, and the flanks commonly dip at 40 degrees, although in some parts of the western flank the dips approach vertical. The komatiite sequence is underlain and overlain by tholeiitic basalts and extensively intruded by sodic granite and rhyolite porphries. The footwall basalt is at least 1,700 m thick and is dominated by fine-grained, massive, metabasalts which show no marked compositional variation. Pillowed and flow breccia horizons are common.

The komatiites range from 13% to 26% Mg and have been subjected to low grade but significant metamorphism, serpentinization and talc carbonate alteration. Ross and Hopkins (1975) divided the ultramafic rocks into four composition types (Table 6). The ultramafics show an overall irregular decrease in magnesium content and an increase in calcium and aluminum upwards. These trends are reflected in an increased abundance of talc- chlorite-carbonate and tremolite-chlorite rocks over the upper half of the sequence. Talc carbonate and serpentine rocks occur in the lower part. The serpentinites contain more than 20% Mg and antigerite is the only serpentine phase.

The komatiite sequence consists of numerous, individual lithological units (Fig. 12). They have been divided by Ross and Hopkins (1975), into two sequences; thin units, which dominate the upper two-thirds of the ultramafic, and thick units which form the lower portion of the ultramafic. Thin units are 0.3 to 7 m thick; rarely exceed 19% Mg and average 14% Mg; have extensive spinifex zones and consist of tremolite chlorite, talc chlorite carbonate or intermediate lithologies. The thick units range from 10 m to 30 m in thickness; show marked differentiation, with increases in Mg towards the base; and may contain spinifex textures in the upper part of each unit. The thin units are chemically and lithologically similar to komatiite lavas described by Barnes et al. (1974) from Mt. Clifford.

	1	2	3	4	5	6	7
SiO_2	48·09 (1·30)*	47·16 (3·27)	45·44 (1·70)	44·00 (2·76)	n.d.	n.d.	n.d.
TiO_2	0.32 (0.09)	0.27 (0.10)	0.17 (0.02)	0.14 (0.03)	0.24	0.17	0.34
Al_2O_3	8.14 (1.48)	5.87 (1.96)	4.06 (0.45)	2.97 (0.89)	3.8	4.0	5.3
Fe_2O_3	2.30 (0.92)	3.92 (1.79)	3.65 (1.02)	4.09 (1.10)			
FeO	8.12 (2.61)	6.13 (1.67)	5.36 (0.85)	4.60 (0.68)			
MnO	0.20 (0.02)	0.17 (0.06)	0.12 (0.04)	0.15 (0.06)			
MgO	23.44 (0.72)	30.96 (3.33)	36.97 (1.09)	42.70 (0.82)	0.13	0.13	0.17
CaO	7.99 (0.78)	5.40 (2.46)	2.69 (1.53)	0.74 (0.75)	30.3	32.8	22.1
Na_2O	0.12 (0.04)	0.05 (0.03)	0.07 (0.03)	0.03 (0.01)	3.8	2.4	5.6
K_2O	0.06 (0.05)	0.02	0.03 (0.01)	0.01	n.d.	n.d.	n.d.
P_2O_5	0.05	0.02	0.01	0.01	n.d.	n.d.	n.d.
Cr_2O_3	0.44 (0.08)	0.35 (0.14)	0.16 (0.04)	0.23 (0.02	n.d.	n.d.	n.d.
S	0.11 (0.14)	0.16 (0.13)	0.42 (0.28)	0.15 (0.10)	0.18	0.17	0.33
Ni (ppm)	1 116 (238)	1 796 (577)	2 578 (1 724)	2 710 (432)	0.09	0.19	n.d.
V	137 (13)	102 (37)		48 (10)	1907	1252	1431
Ba	10 (5)	23 (79)		9 (3)	n.d.	n.d.	n.d.
Cu	56 (51)	31 (18)		12 (9)	n.d.	n.d.	n.d.
Zn	91 (16)	83 (35)		56 (8)	48	44	55
Zr	17 (4)	14 (6)		11 (10)	56	44	72
Cl	129 (69)	150 (168)		75 (37)			
H_2O^+	6.29 (0.87)	5.88 (0.88)	4.54 (2.10)	4.10 (0.73)			
CO_2	0.22 (0.20)	8.02 (3.59)	9.72 (3.11)	17.00 (1.57)			

*Standard deviation in brackets.

1. Average of 14 tremolite-chlorite rocks from the thick meta-picrite. Talc is absent from all samples and MgO content ranges from 22.2-24.7 per c
   Analyst: B.W.Chapple.
2. Average of 33 samples of talc-chlorite-carbonate (dolomite-ankerite) rock. MgO content ranges from 28.0-32.0 per cent. Analyst: B.W.Chapple.
3. Average of 12 samples of talc-carbonate-chlorite rock containing 34-38 percent MgO. Carbonate includes dolomite-ankerite and magnesite. Analyse
   W. M. C. Laboratories.
4. Average of 10 samples of talc-magnesite-chlorite and 2 samples of antigorite rock containing 40-44 per cent MgO. Data for H_2O and CO_2 for talc-
   ate samples only. Analyst: B. W. Chapple.
5. Average of 23 samples from basal komatiite unit, LunnonShoot. Analyst W.Guthrie.
6. Average of 11 samples from basal komatiite unit, Durkin Shoot. Analyst W.Guthrie.
7. Average of 98 samples from "thin units" (Ross & Chappell, 1975). Analyst W.Guthrie.

NOTE: Samples 1 to 4 are from LunnonShoot Environment (Ross & Chappell, 1975).

? Hopkins

Table 6. Average composition of komatiites from Kambalda based on analyses from Ross and Hopkins (1975), and mean results from this study. The groups of Ross and Hopkins are based on mineralogy, whereas groups 5, 6 and 7 represent mean values for thick and thin units from this study.

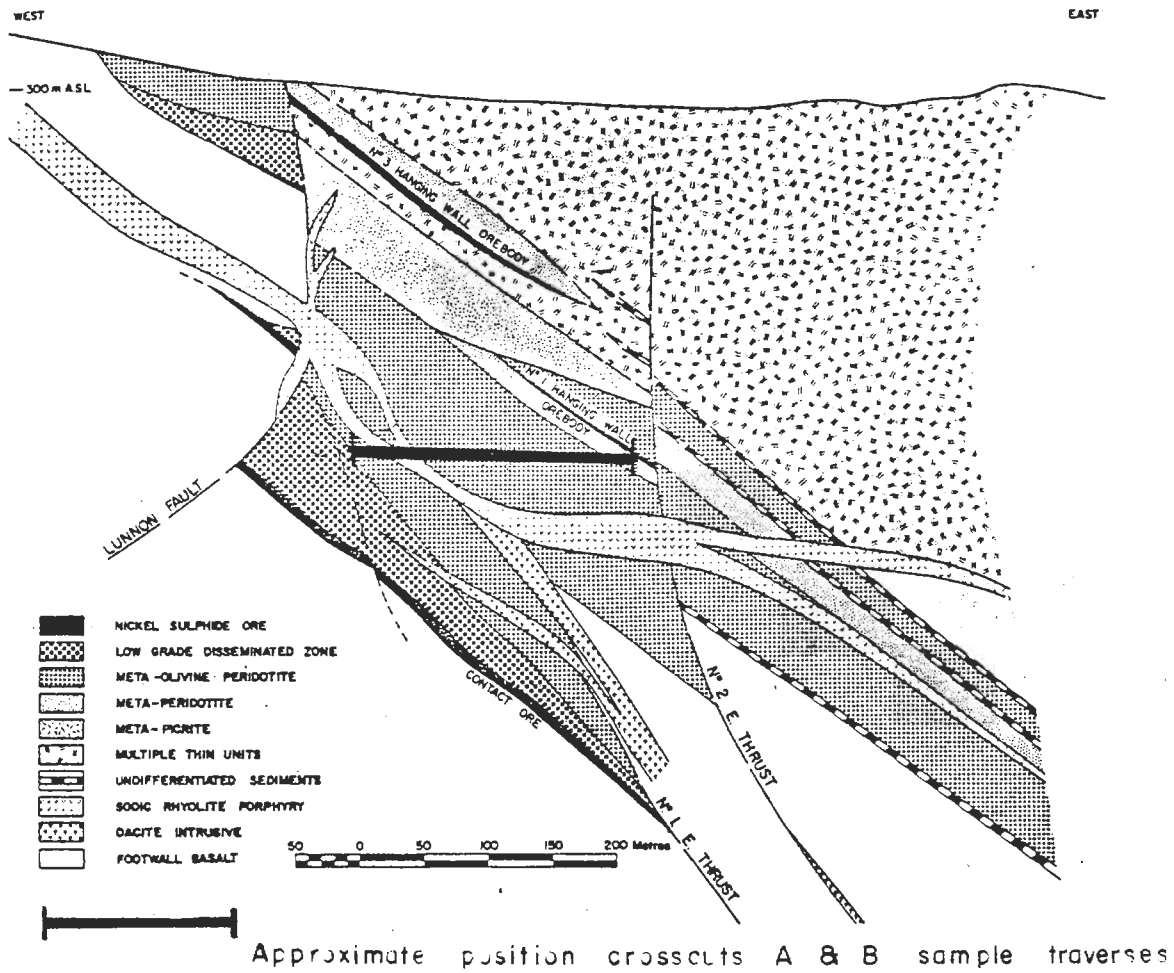

Fig.12 . Cross section through Lunnon Shoot showing relationship of "thin units" to ore bearing "thick units" (peridotites). Approximate position within sequence of sampling traverses A and B is also indicated. Geology is from Ross and Hopkins (1975).

Horizons of sulphide bearing sediments occur within, and at the base of the komatiite sequence. They are well banded; usually less than 5 m thick; occur at contacts between komatiites; are often continuous over hundreds of meters; and are mainly confined to the thick unit section of the sequence. Sulphide sediments seldom occur adjacent to mineralization.

Mineralization occurs as both contact and hanging wall bodies. Contact mineralization often consists of a thin layer of massive sulphides, overlain by a thicker and more continuous layer of disseminated sulphide. Total thickness is usually less than 3 m. Primary sulphide assemblages have pyrrhotite-pentlandite ratios of 2.3:1 (Lunnon Shoot) and 0.8:1 (Durkin Shoot); Ni:Cu ratios average 13:1; and Ni:Co ratios average 54:1. Thin pyrite layers occur within some massive sulphide sections. The disseminated sulphides show a sharp contact with underlying massive sulphides and a distinct contact with the overlying komatiite. The sulphide content ranges from 20 to 65% and increases downwards. Sulphides may form a matrix (Ewers and Hudson, 1972) to silicate and carbonate gangue in the lower part of the disseminated zone. Sulphur nickel ratios are almost identical for both massive and disseminated sulphides at 3.98. There are marked concentrations of spinel phases at the base of the disseminated layer, with significant concentrations of chromite (Fig. 13). However, overall the mean Cr content is slightly depleted in the disseminated sulphides with respect to the komatiite host (mean 1431 ppm - Table 6) and in the massive sulphide the mean Cr value is approximately one-third the Cr content of the host. Zinc (Fig. 13, Table 6) is slightly enriched in massive sulphide and significantly greater (3 times) in the disseminated sulphide than in the komatiite host (approximately 50 ppm).

Hanging wall mineralization occurs at some internal komatiite contacts in the lower part of the sequence. Sulphide concentrations are generally less than 20% and consist of irregular patches or blebs up to 2 cm across, and uniform fine-grained disseminations.

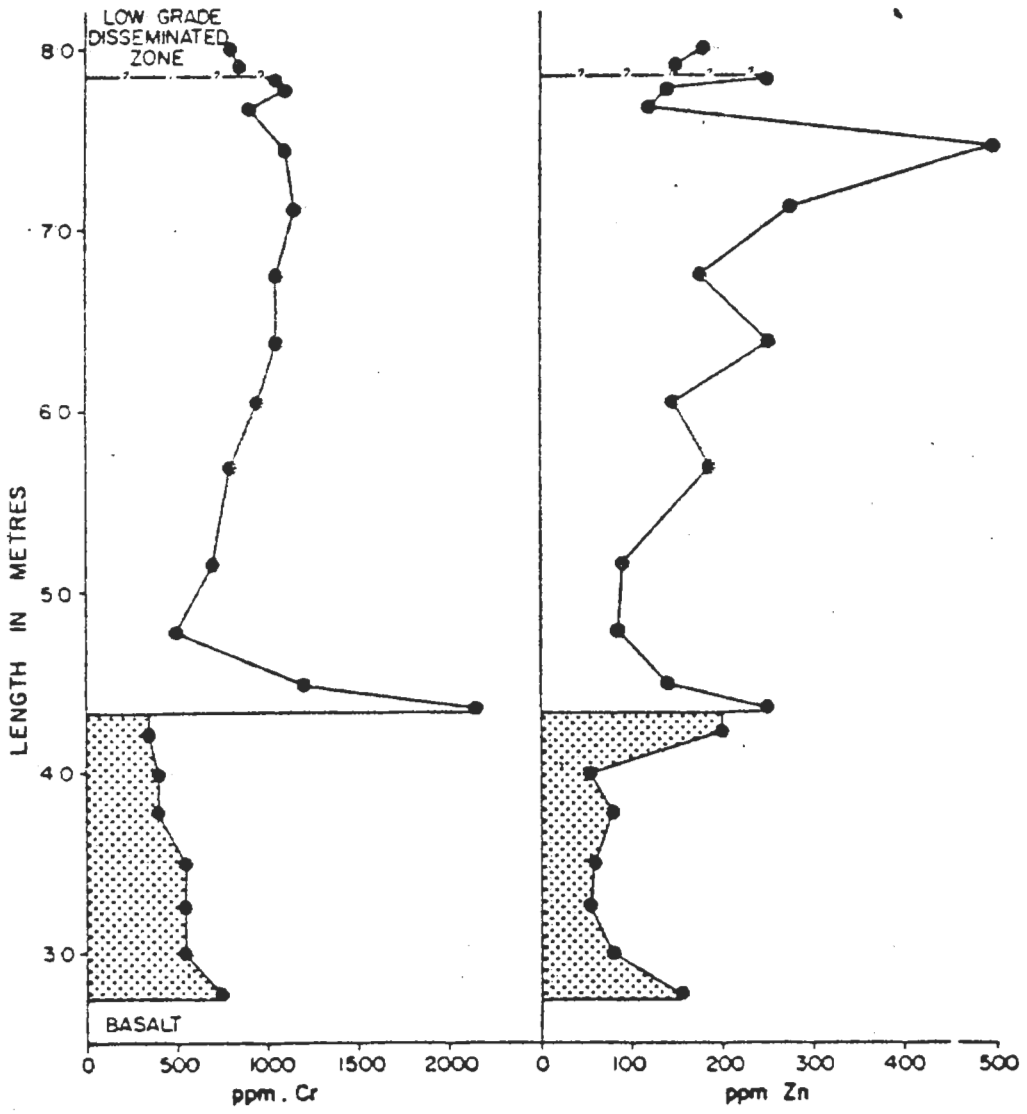

FIG. 13. Profiles for total chrome and zinc in contact sulphides from Lunnon Shoot.
(after Ross and Hopkins, 1975)

Arithmetic means of chemical results and canonical scores for all Kambalda samples; mean values for Lunnon and Durkin Shoots, and for the thin units; values for certain sampling traverses and a drill hole are shown in Table 7. The mean chemical values for all samples from Kambalda are closer to the means for barren komatiites than for mineralized komatiites (Table 3). The mean chromium value falls approximately midway between the mineralized and barren komatiites. These apparent anomalies are caused by the fact that there are two distinct populations within the Kambalda samples corresponding to the thick and thin units of Ross and Hopkins (1975). The thick units are geochemically similar to komatiites from other mineralized areas. Table 7 shows the mean values for thick and thin units, the thick units being represented by Lunnon and Durkin samples. Nickel values for Lunnon and Durkin approximate 2,000 ppm NiP 1,100 ppm Mg 19.0% and Cr 1,200 ppm. The thin units average 233 ppm NiP, 1,252 ppm Ni, 13.3% Mg and 2,223 ppm Cr. Copper, CuP and Al are essentially similar in both groups, but Ca, Zn and Mn are significantly higher in the thin units and CoP is significantly lower. Ni:Cr ratios are 1.65 for Lunnon and Durkin and only 0.56 for the thin units. Ni:NiP ratios vary from 1.42 at Durkin to 2.04 at Lunnon, and 5.37 in the thin units.

Two crosscuts on the 580 level at Lunnon were sampled at regular intervals away from the footwall sulphides. Analyses for both cross cuts are shown in Table 7 and Figs. 14 and 15. Crosscut B samples the full width of the lowermost komatiite unit and the basal part of the second unit (one sample only). In both cross cuts sampling indicates that the basal komatiite consists of high magnesium olivine cumulate rocks, probably olivine peridotite or dunite in the lowermost three quarters of the unit passing upward into less magnesium rich silicate liquid derived rocks, including plate spinifex and tremolite, chlorite rocks. Talc carbonate alteration is more extensive in crosscut B.

Location	No. of Samples	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co	Ni/NiP
Mean-Kambalda	132		456	1439	46	53	2.6	3.6	14.7	67	1958	1237	6.8	30	109	3.15
Mean-Lunnon	23	2.10	982	1907	40	48	2.0	2.7	18.3	56	1213	992	6.3	44	114	2.04
Mean-Durkin	11	1.50	1343	2252	44	44	2.1	1.7	19.8	44	1150	990	6.3	50	115	1.42
Mean-"thin" units	98	3.58	233	1234	48	55	2.8	4.0	13.3	72	2223	1322	7.0	24	107	5.37
Crosscut A																
6 m.	1	0.76	1800	2625	72	80	1.3	0.4	22.8	60	1300	800	6.0	52	100	1.46
12 m.	1	1.47	1137	2100	38	40	1.0	2.2	21.8	50	1400	900	6.0	70	100	1.85
18 m.	1	1.08	975	2200	6	12	1.4	0.6	23.4	60	1300	700	5.5	65	100	2.26
24 m.	1	1.56	887	2150	94	105	0.9	0.7	23.4	50	1400	400	4.6	50	90	2.42
30 m.	1	1.03	1042	2300	32	35	0.9	0.4	23.4	40	1000	750	5.5	65	100	2.21
36 m.	1	0.98	937	2475	4	10	1.1	0.4	23.4	40	900	500	4.9	50	95	2.64
42 m.	1	0.53	1000	2400	10	15	1.3	0.4	22.8	60	900	800	4.9	62	100	2.40
48 m.	1	1.68	1275	2075	8	20	0.9	11.0	15.6	50	900	1050	4.0	55	90	1.63
54 m.	1	1.37	1163	2125	40	45	1.3	1.1	19.6	50	1150	900	6.0	40	100	1.83
60 m.	1	1.86	250	1450	112	120	4.3	4.3	14.2	80	950	1400	8.9	25	110	5.80
67 m.	1	3.98	38	550	8	12	4.7	4.7	12.8	80	1400	1650	9.3	10	105	14.50
Crosscut B																
9 m.	1	1.82	1050	2000	8	10	1.1	1.1	20.6	40	1150	900	5.5	55	120	1.90
18 m.	1	1.10	1550	2550	28	30	1.1	0.1	22.2	40	1000	550	4.8	65	130	1.65
27 m.	1	2.19	1050	2300	8	10	1.2	1.7	20.8	40	1100	730	4.7	55	140	2.19
41 m.	1	2.59	1025	1900	6	12	0.7	8.7	16.0	40	1000	1350	4.4	50	120	1.85
54 m.	1	3.51	525	1225	86	91	2.9	5.6	12.9	70	1850	1650	7.9	35	150	2.33
58 m.	1	4.90	50	500	2	5	4.6	6.0	12.1	80	1450	1550	8.8	5	130	10.00
60 m.	1	1.06	5800	6800	240	290	1.6	2.5	15.6	40	1000	1230	7.4	120	200	1.17
Rotary Hole																
30 m.	1	3.13	613	1425	86	83	2.4	4.7	12.6	60	2450	1550	8.2	45	110	2.32
36.1 m.	1	3.23	363	1200	41	50	2.6	4.4	13.2	60	2300	1350	7.1	33	95	3.30
42.2 m.	1	3.65	258	1075	40	48	3.2	4.1	12.8	60	2450	1450	8.0	28	105	4.17
48.3 m.	1	3.17	413	1225	60	70	2.6	4.7	12.8	60	2100	1400	7.1	38	100	2.97
54.4 m.	1	3.21	400	1250	45	50	2.8	4.3	13.2	60	2250	1350	7.4	35	105	3.12
60.5 m.	1	2.58	488	1400	56	55	2.4	4.4	14.1	50	1450	1500	6.6	38	100	2.87
66.6 m.	1	2.63	488	1425	43	48	2.4	3.8	14.1	50	1550	1300	6.6	38	100	2.92
72.7 m.	1	3.10	419	1325	39	48	2.4	4.1	13.7	50	1950	1400	6.8	35	100	3.16
78.8 m.	1	3.12	375	1250	46	53	2.6	4.7	13.2	60	1950	1350	7.1	33	105	3.33
84.9 m.	1	3.11	388	1275	48	50	2.8	3.8	13.7	50	1950	1350	6.9	33	100	3.28
91.0 m.	1	3.59	275	1150	40	53	2.6	5.0	12.4	70	2550	1450	7.7	28	105	4.18
97.1 m.	1	3.63	338	1100	49	63	3.4	7.8	10.6	90	2550	1800	7.7	33	115	3.25
103.2 m.	1	2.12	775	1575	25	35	3.5	3.8	14.5	50	1350	1000	5.8	48	95	2.03
109.3 m.	1	2.20	450	1425	36	38	1.9	4.1	14.5	60	1250	1250	6.4	35	100	3.17
115.4 m.	1	3.78	163	1225	45	50	3.3	3.8	13.2	60	2550	1050	7.7	20	105	7.51
121.5 m.	1	3.83	163	1125	29	40	2.9	5.2	12.8	60	2200	1450	7.1	23	105	8.27
127.6 m.	1	4.19	150	1075	36	53	3.3	7.2	11.0	70	2450	1550	7.7	15	105	7.17
133.7 m.	1	3.73	238	1175	50	48	2.9	5.9	11.9	60	2400	1450	7.1	23	105	4.93
139.8 m.	1	3.63	263	1200	54	60	2.9	5.8	12.5	70	2350	1550	7.4	28	115	4.56
145.9 m.	1	3.89	163	1125	59	63	2.9	4.3	12.8	70	2300	1250	7.7	18	115	6.90
152 m	1	4.05	163	1225	45	63	2.5	4.1	13.2	70	2300	1500	7.4	18	115	7.51
158.1 m.	1	3.84	138	1200	56	60	2.8	3.6	13.2	80	2450	1400	7.4	18	115	8.70
164.2 m.	1	4.44	88	1050	58	68	2.9	4.0	13.2	70	2450	1400	7.7	10	115	11.93

Table 7. Komatiite analyses, Kambalda, with canonical scores, Ni/NiP and Ni/Cr ratios. Mean values for Kambalda, Lunnon, Durkin and thin units show the heterogeneous nature of the ultramafic sequence. Crosscuts A and B are from Lunnon Shoot The last two samples in Crosscut A and samples 5 and 6 in Crosscut B represent the silicate liquid portion of a thick unit. Sample 6 (60 m.) is from the base of a second, overlying thick unit. The rotary hole samples represent mean values for part of the thin unit sequence.

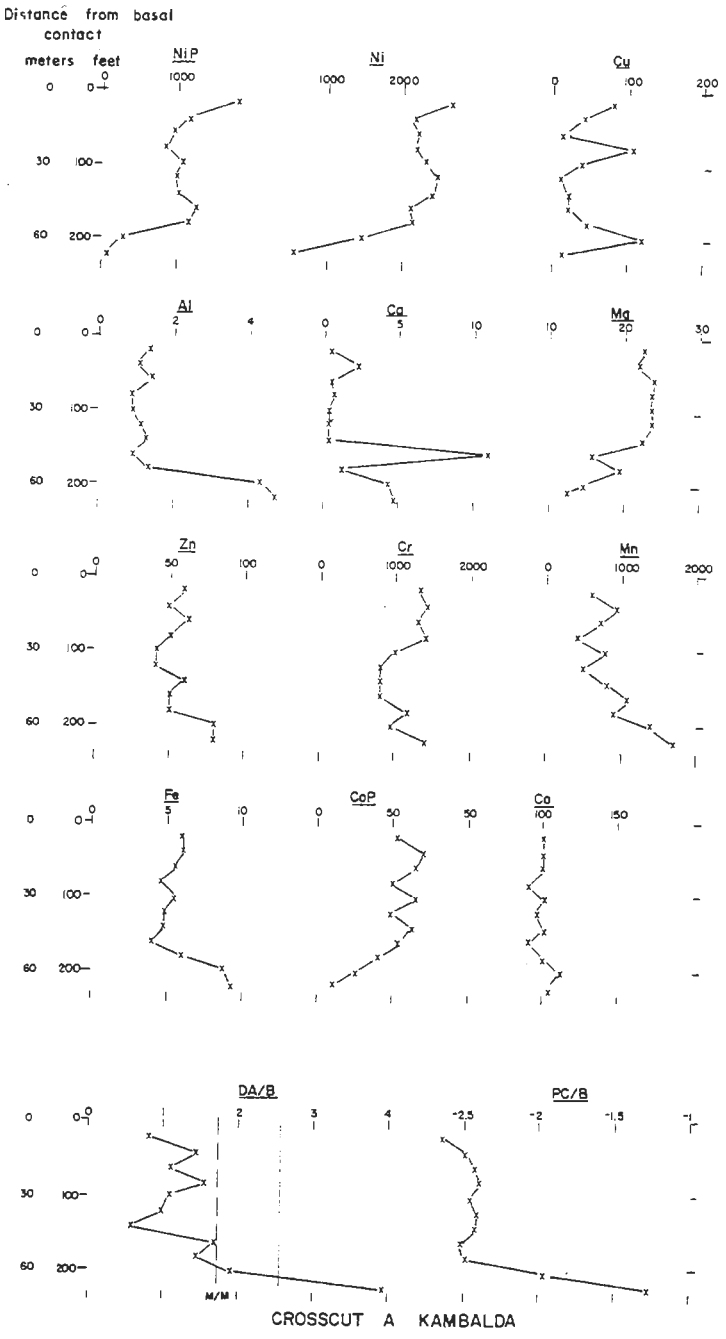

Fig. 14. Plot of geochemical results for samples from Crosscut A, Lunnon Shoot, Kambalda. DA/B and PC/B indicate scores for samples from Discriminant Analysis B and Principal Component B respectively. The samples represent a single thick unit which overlies nickel sulphides.

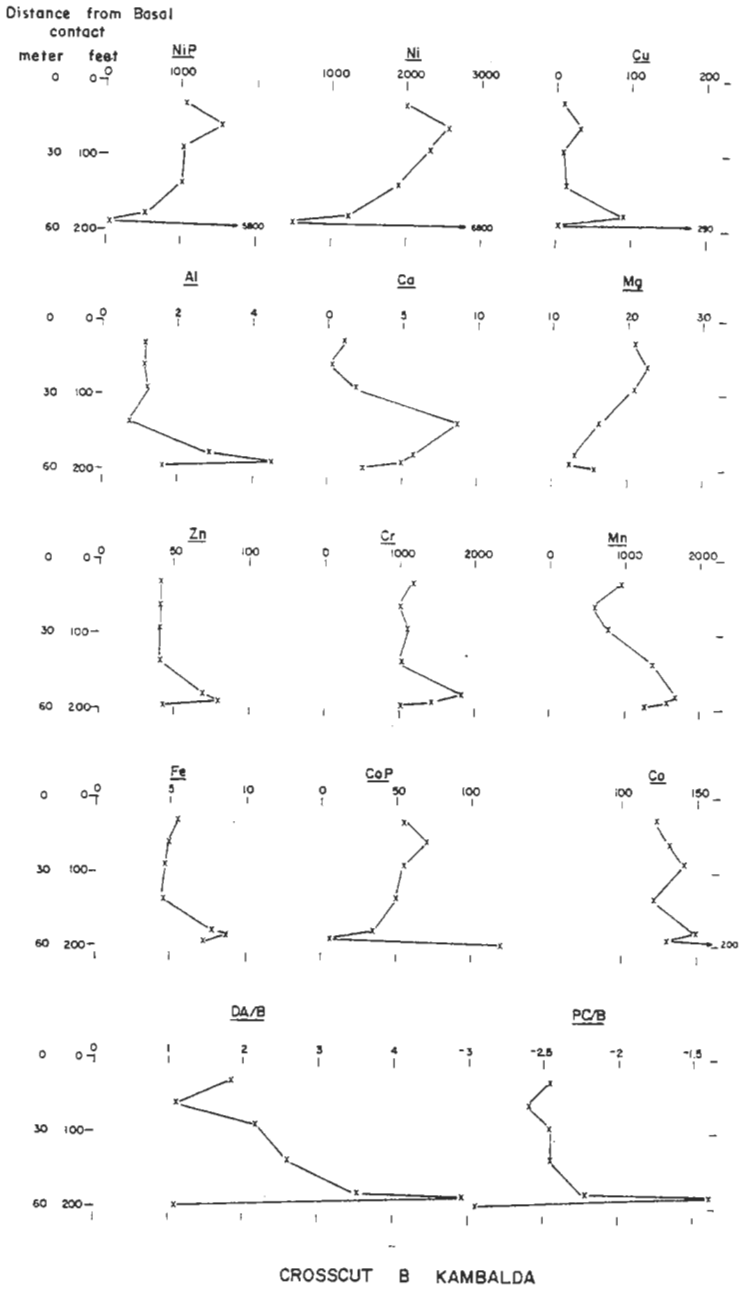

Fig. 15 . Plot of geochemical results for samples from Crosscut B, Lunnon Shoot, Kambalda. DA/B and PC/B indicate scores for samples from Discriminant Analysis B and Principal Component B respectively. The samples represent a single thick unit which overlies nickel sulphides, except for the sample at 60 m. which is the base of a second thick unit.

Note that the average value of 19% Mg for Lunnon and Durkin shoots (Table 7), although apparently low for peridotites, is in part caused by the inclusion of spinifex and other low magnesium samples from the upper parts of the thick unit. The spinifex rocks may classify as either Mineralized or Barren depending on the nickel and chromium values. Nickel, NiP and Mg tend to be fairly constant in the lowermost two-thirds of this komatiite unit but decrease rapidly in the upper one-third of the unit. There is a slight increase in Ni, NiP and Mg content in the central part of the unit. Manganese and Fe both show a tendency to decrease in value, and CoP which is highly correlated with NiP, increases towards the base of the unit. Cobalt is constant in both olivine cumulate and silicate liquid parts of the komatiite. In crosscut A, a high negative correlation between Ca and Mg is illustrated in the sample 30 m above the basal contact where a sharp increase in Ca content, due to talc carbonate alteration resulted in a significant decrease in the Mg content. In crosscut B, where Ca content overall is higher than in cross cut A, the average Mg content tends to be significantly lower. Crosscut A showed a considerably higher degree of talc carbonate alteration than B. Within the thin units, one rotary hole was sampled between depths of 30 and 170 m, using 6.5 meter composite samples. Although this method yielded reliable average geochemical data for the overall composition of the thin units, because of the wide intervals used, the results do not help to define the chemistry or width of individual units.

The discriminant functions derived from Analyses A and B both classify samples from Lunnon and Durkin shoots as Mineralized, and most of the remaining samples from the upper thin units as Barren. A frequency distribution histogram of canonical scores from Analysis B (Fig. 54), is polymodal, the modes with values of less than 2.2 representing Lunnon and Durkin shoot sample scores. Mean canonical value for Lunnon samples is 2.12,

Durkin samples 1.50 and thin unit samples 3.58. In Figs. 14 and 15, canonical scores are plotted against distance from the sulphide ore zone on crosscuts A and B at the Lunnon Mine. Both crosscuts penetrate the full width of the lowermost komatiite unit, and in cross cut B the highest score is from a sample of the basal section of the overlying or second komatiite unit. In crosscut B canonical scores increase with distance from the mineralization, but in cross-cut A scores remain approximately constant for four-fifths of the komatiite and only increase in the uppermost one-fifth (silicate liquid derived) of the komatiite.

Discriminant Analysis D (Fig. 5) places Kambalda within the Barren zone. However, mean canonical score for Lunnon plus Durkin is indicated by "A" in Fig. 5 and is well within the "definite" Mineralized zone.

4.1.2 Windarra South

Windarra South is a small to moderate sized, nickel sulphide mine. (Figs. 16 and 2). Geological ore reserves at Windarra South vary from 10.5 M tons at 1.26% Ni and o.06% Cu, to 3.5 M tons at 2.05% Ni and 0.09% Cu, depending on cut-off grade. Ore occurs at and near a relatively flat dipping, basal, ultramafic contact with banded iron formation. As distinct from Windarra (see Section A3) the ore occurs mainly at the basal ultramafic contact, and not at internal contacts. Bedrock at Windarra South is completely obscured by approximately 30 m of alluvial, water bearing, overburden.

The banded iron formation is very thin, with an average width of 5 to 10 m and a maximum width of 20 m. This has been caused by granite intrusion. The komatiite sequence is heterogeneous, less deformed than at Windarra and ranges up to 300 m in thickness. On the basis of lithology and chemistry (Tables 8 and 9), the sequence can be subdivided into three units, designated A, B and C.

The ore is associated with unit A (Figs. 17-22), the lowermost and most

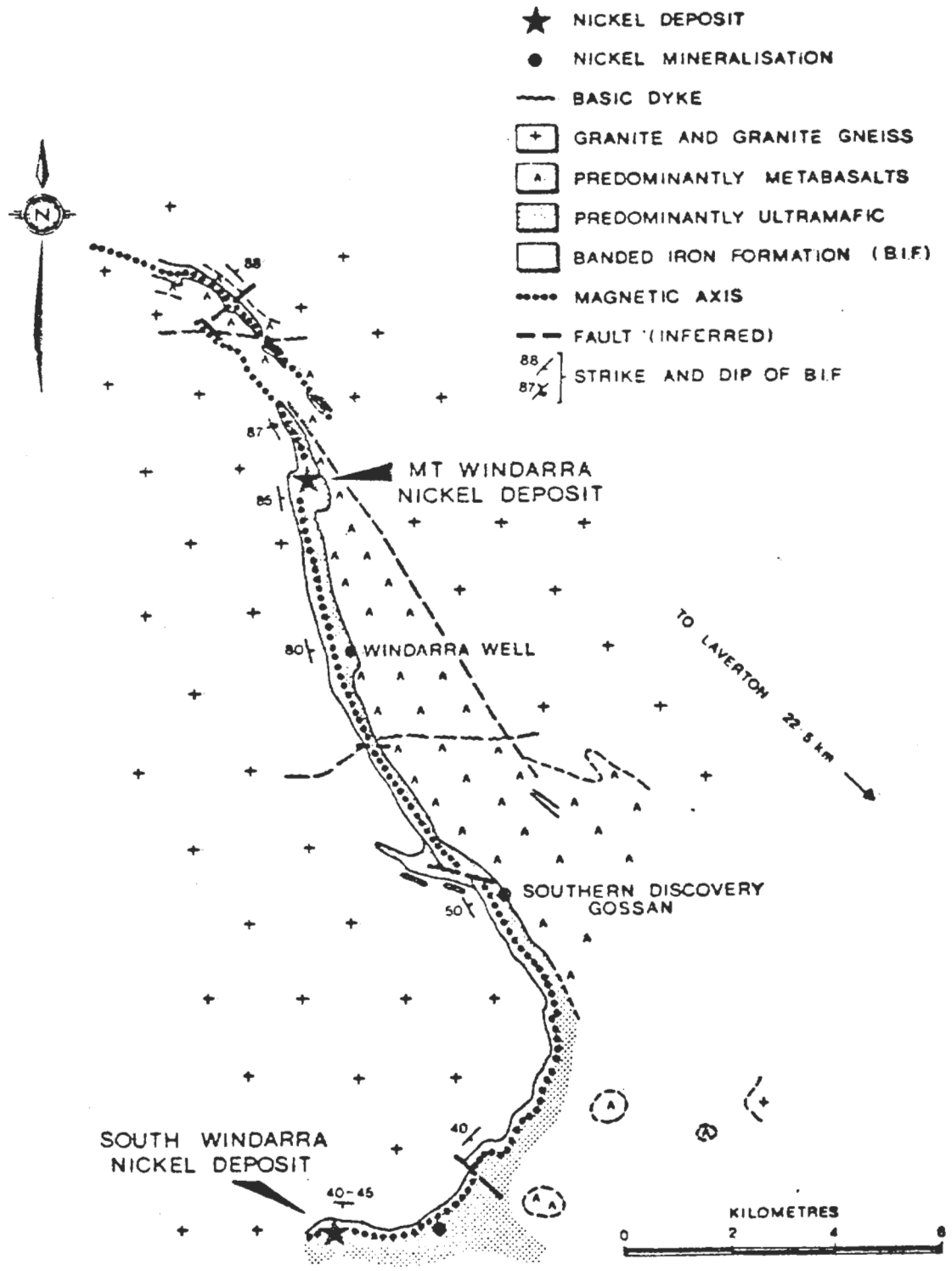

Fig. 16. Geological plan of Windarra Nickel Province (from Roberts, 1975).

Section	Hole No.	Depth Meters	DA/B Canonical Score	Number of Samples	Unit	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co	Ni/NiP	Ni/Cr
S	27	99.1-120.1	1.58	8	B	703	1622	14	18	2.1	2.6	16.8	77	1162	881	3.8	38	87	2.31	1.39
		120.1-133.5	1.46	4	B	388	1756	4	6	2.2	0.7	18.2	90	975	525	4.7	26	63	4.53	1.84
		140.9-144.2	0.39	4	A	3518	4650	74	84	1.0	0.9	16.1	182	1362	1075	5.3	121	173	1.32	3.41
S	58	108.8-258.2	3.45	18	C	276	1140	34	40	3.4	5.1	11.9	89	2391	1328	6.5	23	103	4.13	0.48
		258.2-283.5	0.84	1	B	388	1275	76	73	2.5	3.1	14.9	60	1600	1050	6.2	35	105	3.28	0.80
		283.5-306.4	0.46	9	A	1843	2669	31	34	0.9	1.0	21.4	84	1533	872	4.7	57	81	1.45	1.74
N	53	208-361	4.17	18	C	138	1102	37	47	3.7	4.9	12.5	84	2417	1386	6.4	18	108	8.0	0.46
		375-462	2.77	8	B	405	1300	33	37	3.0	3.8	14.1	118	2220	1294	5.9	33	109	3.2	0.59
		465-473	1.31	4	A	1150	2181	18	21	2.4	1.4	17.1	82	1162	700	4.0	47	102	1.9	1.88
N	29	92-165	2.74	13	B	372	1136	38	45	3.9	3.6	13.3	138	2146	1315	6.5	80	105	3.1	0.53
		165-175	1.60	3	A	1391	1114	13	37	0.7	2.1	21.0	60	1233	850	4.3	72	123	1.6	1.80
		179-184	2.61	3	B	646	1225	35	44	3.0	4.1	15.7	67	1333	1183	6.2	39	112	1.9	0.92
		220-269	0.70	16	A	2190	2932	54	59	1.4	1.6	17.8	121	1621	1168	5.4	74	114	1.3	1.81
I	22	62.5-67.1	3.27	8	B	784	1368	44	53	1.7	5.5	14.7	41	1950	1206	5.2	64	120	1.7	0.7
		67.1-76.5	2.44	14	B	490	1103	30	34	3.5	4.4	13.7	96	1023	1318	5.9	38	112	2.3	1.08
		76.5-99.7	3.32	18	B	509	1104	66	73	2.8	4.1	14.2	69	1729	1508	6.5	43	122	2.2	0.64
		116.1-137.2	0.49	19	A	1842	2655	27	29	0.8	1.1	19.2	115	1181	1000	4.6	66	93	1.4	2.25
		145.4-154.3	1.48	9	A	1107	1930	81	86	2.3	1.7	15.6	114	1750	928	5.0	48	103	1.7	1.10
		154.3-167.7	0.34	8	A	2362	2561	58	55	1.0	0.7	16.9	146	1440	1236	5.6	81	120	1.1	1.78
I	32	81.4-146.9	2.67	6	B	556	1270	55	68	3.2	5.0	14.2	113	2141	1416	7.2	41	112	2.3	0.59
		146.9-154.5	1.68	3	A	1150	2041	24	28	1.2	2.0	20.0	63	1291	817	4.4	68	120	1.8	1.58
		182.9-218.0	2.53	8	B	533	1206	67	75	3.0	5.3	13.6	126	1965	1700	7.4	41	113	2.3	0.61
		218.0-235.3	1.08	7	A	2410	3207	122	149	1.6	3.9	16.5	138	1485	1564	6.4	89	148	1.3	2.61
E	52	174.7-177.4	2.60	2	B	450	1425	20	22	2.1	5.4	15.1	75	2050	1200	5.6	31	93	3.2	0.7
		250.3-286.9	2.14	12	A	766	2400	41	47	2.2	3.7	15.1	31	1994	1212	5.3	32	100	3.1	1.2
E	45	63.1-93.6	3.45	3	C	217	1272	22	34	2.9	3.3	14.7	83	2500	1183	6.4	20	101	6.0	0.52
		99.7-114.6	1.98	3	B	567	1567	18	26	2.1	2.5	16.0	93	1500	833	4.5	29	87	2.8	1.04
		166.8-183.5	1.98	3	B	204	1766	26	31	2.4	3.0	14.2	303	1667	933	5.2	18	87	8.7	1.06
		183.5-211.0	1.54	4	A	1325	2787	64	90	2.3	2.9	14.5	108	1525	1400	5.5	42	118	2.1	1.83
E	7	66.8-131.7	0.92	16	A	2698	3726	64	68	1.0	0.4	20.3	73	1793	669	5.6	92	135	1.4	2.08
Z	51	125-156.7	2.30	20	A	948	2141	82	90	1.8	8.1	15.1	65	1745	1130	5.0	58	125	2.3	1.23
Windarra Unit A Mean			1.18	134		1756	2737	57	63	1.3	1.8	17.7	95	1576	1047	5.1	67	115	1.56	1.74
Windarra Unit B Mean			2.60	99		517	1278	41	47	3.5	4.0	14.5	94	1693	1275	6.0	40	107	2.47	0.75
Windarra Unit C Mean			3.78	39		208	1134	34	43	3.5	4.9	12.5	86	2411	1343	8.1	20	106	5.45	0.47

Table 8 : Summary of geochemical data and mean canonical scores for the three main komatiite associations at Windarra South.

Note that the following determinations increase towards the base of the entire sequence, that is from Unit C through Unit A - NiP, Ni, CuP, Cu, Mg and CoP, whereas the following determinations decrease - Al, Cu, Cr, Mn and Fe. Unit A, which is the main nickel sulphide host, has Ni/Cr and Ni/NiP ratios of 1.74 and 1.56 respectively.

Mg is lower in the Windarra South host than in comparable hosts in the Kalgoorlie-Norseman Nickel Province. Zn is also relatively high compared to other nickel provinces. These differences may be diagnostic features of the Windarra Nickel Province.

HOLE WSD 22

Meters	Depth Feet	Canonical Score	NiP	Total Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO2	CoS	Co	Ni/Cr	Ni/Ni
62.5	205-208	3.83	763	1300	124	145	1.70	6.65	13.80	50	1900	1500	5.10	0.20	88	150	0.68	1.7
	208-210	3.35	750	1225	24	30	1.60	8.90	14.40	50	2050	1650	4.80	0.18	55	105	0.60	1.6
	210-212	3.17	763	1325	24	33	2.10	6.15	14.80	40	1550	1400	5.20	0.26	63	120	0.85	1.7
	212-213	3.78	813	1425	26	33	1.60	5.35	14.60	60	3500	1350	6.00	0.20	65	125	0.41	1.7
	213-214	3.42	750	1375	29	33	1.60	5.35	15.20	30	1650	1100	4.80	0.20	58	115	0.83	1.8
	214-216	3.39	800	1400	30	35	1.60	5.35	14.80	30	1675	1150	5.00	0.20	63	115	0.84	1.7
	216-218	3.02	838	1475	44	55	1.85	3.05	15.20	30	1375	750	5.00	0.22	60	115	1.07	1.7
	218-220	3.26	800	1425	54	60	1.70	3.00	15.00	40	1900	750	5.40	0.22	60	120	0.75	1.7
	220-222	2.37	750	1325	54	58	2.40	4.40	15.40	50	1250	1000	5.50	0.28	58	110	1.06	1.7
	222-225	2.48	725	1325	46	50	2.85	5.20	14.60	60	1425	1250	5.20	0.28	53	110	0.93	1.8
	225-228	2.40	625	1225	58	65	1.85	5.70	14.00	70	1075	1250	5.20	0.24	48	115	1.13	1.9
	228-230	2.52	850	1375	59	58	1.85	4.10	14.80	50	1275	1000	5.40	0.24	63	120	1.07	1.6
	230-232	1.99	875	1375	46	45	2.25	3.60	15.20	50	1000	950	6.00	0.26	65	120	1.38	1.5
	232-234	2.36	688	1225	34	38	3.25	3.20	16.00	50	1225	1050	6.30	0.41	58	120	1.00	1.7
	234-236	2.64	788	1325	41	43	2.50	3.30	15.20	40	1325	900	6.00	0.26	60	120	1.00	1.6
	236-238	2.56	813	1250	41	48	2.75	4.10	15.00	50	1250	1150	6.00	0.22	53	125	1.00	1.5
73.2	238-240	2.22	613	1175	35	40	2.25	6.00	14.00	60	800	1600	5.20	0.25	45	120	1.47	1.9
	240-242	2.61	38	750	2.5	5	6.80	3.55	12.40	160	750	1750	6.80	0.20	5	100	1.00	19.7
	242-245	2.98	25	675	2.5	5	5.30	4.65	11.80	110	600	1500	6.00	0.22	5	95	1.13	27.0
	245-247	4.00	25	975	2.5	5	2.70	6.00	12.00	90	975	1750	5.80	0.30	5	115	1.00	39.0
	247-249	2.91	25	925	2.5	5	3.40	6.00	12.20	190	825	2000	6.00	0.32	5	105	1.12	37.0
	249-251	1.90	25	525	2.5	5	9.35	1.80	9.10	320	550	1300	6.70	0.44	5	90	0.95	21.0
76.5	251-254	3.88	38	1000	4	8	2.85	6.30	12.60	70	875	1850	5.80	0.22	5	115	1.14	26.3
	254-256	2.52	600	1100	165	188	2.40	5.50	14.80	90	1100	1900	6.60	0.28	53	135	1.00	1.8
	256-259	3.26	100	775	23	35	4.25	4.90	13.20	150	1175	1800	8.40	0.53	13	140	0.66	7.7
	259-264	2.63	263	950	56	63	3.25	3.90	13.90	140	1150	2150	7.70	0.41	23	140	0.83	3.6
81.1	264-266	3.77	38	725	31	25	3.40	6.30	12.20	130	1275	1650	8.60	0.44	8	135	0.69	19.1
89.0	292-295	4.46	213	725	96	115	3.60	4.95	13.00	80	2250	1450	8.30	0.44	25	145	0.32	3.4
	295-297	3.50	513	1075	133	158	3.50	4.40	14.80	50	1425	1650	7.70	0.41	45	150	0.75	2.1
	297-299	3.27	388	900	98	120	3.25	4.50	13.60	50	1150	1850	7.40	0.41	38	125	0.78	2.3
	299-301	3.70	613	1075	129	143	2.50	4.25	13.60	40	1625	1650	6.80	0.32	58	135	0.66	1.7
	301-304	3.57	713	1075	120	110	2.50	4.10	14.60	30	1650	1650	5.80	0.32	58	115	0.65	1.5
	304-307	2.98	850	1200	116	108	2.50	3.60	14.80	30	1175	1500	6.30	0.30	68	125	1.02	1.4
94.5	307-310	3.42	325	850	36	38	4.25	3.05	11.50	80	2375	1250	5.80	0.30	28	95	0.36	2.6
	310-313	4.64	25	50	11	18	5.80	1.65	0.62	30	100	250	1.00	0.12	5	25	ND	ND
	313-317	3.37	838	1300	58	53	2.00	4.30	13.60	40	2250	1150	5.50	0.22	63	110	0.58	1.5
	317-319	3.40	913	1475	40	40	1.85	3.05	15.20	80	4200	1150	5.50	0.24	63	115	0.35	1.6
	319-321	2.74	850	1425	28	30	1.85	3.05	26.00	40	1700	1150	5.20	0.24	58	105	0.84	1.6
	321-323	2.78	775	1325	20	23	1.85	2.60	16.00	50	2125	1150	5.50	0.26	58	100	0.62	1.7
	323-325	2.53	688	1325	16	20	1.85	2.30	16.00	50	1575	1050	5.00	0.24	50	100	0.84	1.9
99.7	325-327	2.71	925	1575	19	28	1.85	2.60	16.00	50	2050	1150	5.20	0.24	63	105	0.72	1.7
116.1	381-384	0.48	225	1575	2.5	5	3.00	1.75	14.40	210	650	1000	3.00	0.08	10	70	2.42	7.0
	384-387	-0.21	1525	2125	18	20	0.60	0.03	19.00	150	875	950	3.20	0.06	68	95	2.42	1.3
	387-390	-0.40	1875	2325	15	18	0.75	0.02	19.50	220	1400	1350	4.50	0.06	73	95	1.66	1.2
118.8	390-393	0.45	1175	1950	9	10	0.47	0.50	18.00	110	925	750	2.80	0.05	48	80	2.11	1.6
	393-397	1.27	450	1575	2.5	5	0.90	1.45	16.60	100	1025	750	2.00	0.05	18	55	1.54	3.5
	397-401	-0.31	963	1925	8	10	0.60	0.02	19.50	200	1075	1000	3.20	0.06	38	75	1.79	2.0
	401-404	ND	2000	2300	36	33	0.58	0.95	20.30	430	1325	1250	3.80	0.08	63	90	1.73	1.1
	404-407	ND	1950	2300	8	8	0.63	2.75	19.50	790	1350	1800	3.70	0.09	60	95	1.70	1.1
	407-411	0.49	1850	2300	5	5	0.68	1.90	19.50	110	1250	1300	3.70	0.06	63	95	1.84	1.2
	411-415	0.76	1688	2250	3	5	0.71	2.25	19.50	90	1200	1650	4.10	0.08	58	90	1.88	1.3
	415-420	0.18	1875	2375	16	18	0.70	1.95	20.00	130	1125	1750	4.60	0.09	58	90	2.11	1.2
	420-423	0.58	2250	2500	9	8	0.64	0.95	21.80	50	1150	700	5.00	0.06	65	95	2.17	1.1
	423-425	0.65	2200	2500	2.5	5	0.87	0.80	21.00	70	1375	1050	5.00	0.06	60	85	1.91	1.1
	425-429	1.11	1588	2450	2.5	5	0.85	0.88	20.00	50	1400	850	5.00	0.10	63	85	1.75	1.5
	429-432	1.43	1475	2450	2.5	5	0.77	0.47	21.00	30	1225	450	5.00	0.08	58	90	2.00	1.6
	432-437	0.89	1413	2550	3	5	0.77	0.33	21.00	50	1350	450	5.80	0.08	73	100	1.89	1.8
	437-440	0.98	1500	2400	2.5	5	0.82	1.00	19.00	50	1300	650	7.40	0.08	73	95	1.85	1.6
	440-443	0.91	2500	2950	2.5	5	0.43	0.65	21.00	30	1275	550	6.60	0.03	83	85	2.31	1.1
	442-445	0.84	2400	2850	21	23	0.25	1.45	19.80	40	1125	1000	6.30	0.03	83	90	2.53	1.1
	445-447	-0.47	2900	4300	121	128	0.39	2.00	19.00	250	1250	1550	5.00	0.04	100	115	3.44	1.4
137.2	447-450	-0.31	6350	7100	260	258	2.00	1.80	15.20	200	1475	1250	5.80	0.10	153	175	4.81	1.1
145.4	477-480	1.76	675	1975	178	180	3.00	1.45	14.80	110	1750	800	5.20	0.38	43	105	1.13	2.9
	480-483	1.93	1163	1925	288	325	3.00	1.50	14.40	120	1875	850	5.20	0.38	48	115	1.04	1.6
	483-488	1.80	913	2000	75	73	3.00	0.95	15.60	100	2375	650	5.20	0.38	35	95	0.84	2.1
	488-491	1.67	1075	1925	48	48	1.85	2.90	15.20	90	1675	900	4.50	0.25	43	95	1.15	1.7
	491-493	1.26	1375	2000	46	43	1.60	2.00	16.30	90	1475	900	4.80	0.24	55	100	1.36	1.4
	493-497	0.99	1800	2400	46	43	1.50	1.80	17.00	110	1525	1100	5.20	0.22	68	115	1.62	1.3
	497-502	1.15	1175	1850	19	20	1.60	1.45	17.00	130	1750	1050	5.60	0.24	55	105	1.57	1.3
154.3	502-506	1.41	1100	1675	20	20	1.75	2.30	16.00	120	1750	1150	5.00	0.22	53	100	1.06	1.5
	506-508	1.36	688	1625	10	18	3.50	0.88	14.00	160	1525	950	4.40	0.22	30	95	0.96	1.5
	508-512	0.45	1325	1975	25	28	1.40	0.80	16.50	180	1375	1150	5.50	0.18	53	100	1.06	2.3
	512-516	0.44	2000	2375	40	38	1.50	1.15	19.00	170	1675	1350	5.50	0.24	73	110	1.44	1.4
	516-521	0.82	1800	2225	19	23	1.15	0.88	19.00	140	1575	1150	5.00	0.15	75	115	1.41	1.1
	521-523	0.19	2050	2725	28	33	1.05	0.60	19.00	140	1375	1250	6.30	0.12	75	110	1.98	1.3
	523-526	0.42	1825	2300	19	25	0.95	0.17	20.00	130	1475	1150	5.20	0.12	63	100	1.56	1.2
	526-531	0.47	2550	3000	39	48	0.95	0.22	19.50	130	1425	1450	5.20	0.10	83	125	2.10	1.1
	531-536	0.21	2700	3250	78	85	0.95	0.48	19.50	140	1400	1100	5.80	0.10	83	120	2.32	1.2
	536-540	0.16	4650	5200	213	218	0.85	0.95	19.00	140	1225	1200	6.30	0.08	140	180	4.24	1.1
	540-545	ND	1.37%	1.42%	1200	1300	0.50	145	1480	120	1325	1450	15.20	0.04	410	445	ND	ND
167.7	545-550	ND	1.28%	1.35%	1013	1238	1.05	115	1440	130	3250	1250	16.00	0.12	335	450	ND	ND

Table 9 . Geochemical analyses, canonical scores (B), Ni/Cr and Ni/NiP ratios for komatiites from hole 22 at Windarra South. The ultramafic sequence was sampled using 81 composite pulps, each representing a drill hole length of 0.3 to 1.5 m. These analyses show detailed chemical relationships of Units A and B, and illustrate the composite or heterogeneous nature of the Windarra South komatiite sequence. Nickel sulphide mineralization occurs at and below 137.2 and 167.7 m., and several mineralized thick unit komatiites are present. Note that thick unit (or units) above 137.2 m., contain more NiP, Ni and Mg than the thick units below that depth. Thus, in this instance the most ultramafic and nickel rich unit is not at the base of the sequence.

magnesium rich komatiite. This unit was described by Roberts (1975) as a serpentinite, consisting primarily of antigorite pseudomorphs after orthopyroxene. The chemistry however, shows a high magnesium content and indicates that the original komatiite was a peridotite and not a pyroxenite. Carbonatization and steatization varies from partial (serpentine-talc-carbonate) to complete (talc-carbonate schists). Tremolite-antigorite assemblages represent the less magnesium rich, upper section of the original ore bearing thick unit.

Chlorite rich ultramafics (units B and C - Figs. 18 to 22) occur away from sulphide mineralization and are interpreted as consisting of many individual komatiites, probably lavas, that are analogous to the thin units at Kambalda. The komatiite sequence continues at depth but the ore bearing unit thins rapidly and changes in chemical character.

Felsic porphyry dykes and lenses which intrude the komatiites are more common than at Windarra. Mafic intrusives, now coarse-grained amphibolites, also intrude the sequence.

Mineralization occurs over an east-west strike length of 1280 m and dips at 40 to 45 degrees south (Roberts 1975). Ore occurs in several lenses, individually up to 230 m in length and up to 25 m in thickness. No ore occurs at depths greater than 300 m.

Most of the ore can be classified as disseminated (rarely matrix), and lower grade disseminated mineralization is more common than at Windarra. Sulphide content often tends to increase towards the basal untramafic-banded iron formation contact where narrow, banded, massive sulphide lenses may occur. Primary mineralogy is pyrrhotite-pentlandite, but the bulk of the ore is supergene violarite. Chromitiferous magnetite is associated with the primary sulphides. Nickel: copper ratio is 22:1 for the ore at 1% Ni cut-off.

On most cross sections (Figs. 18 to 22) one hole intersected ore or substantial nickel sulphide mineralization and one hole, usually down

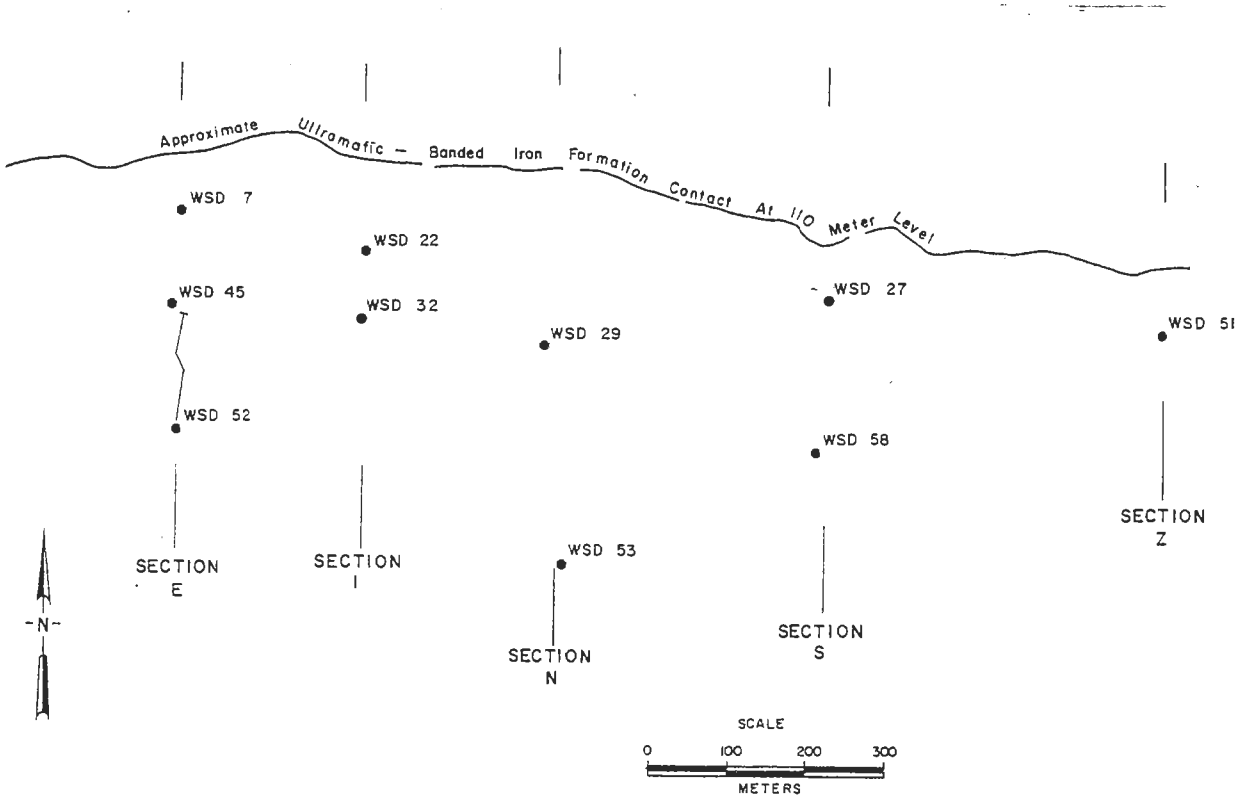

Fig. 17 . Plan of Windarra South showing location of drill holes sampled and sections referred to in the text.

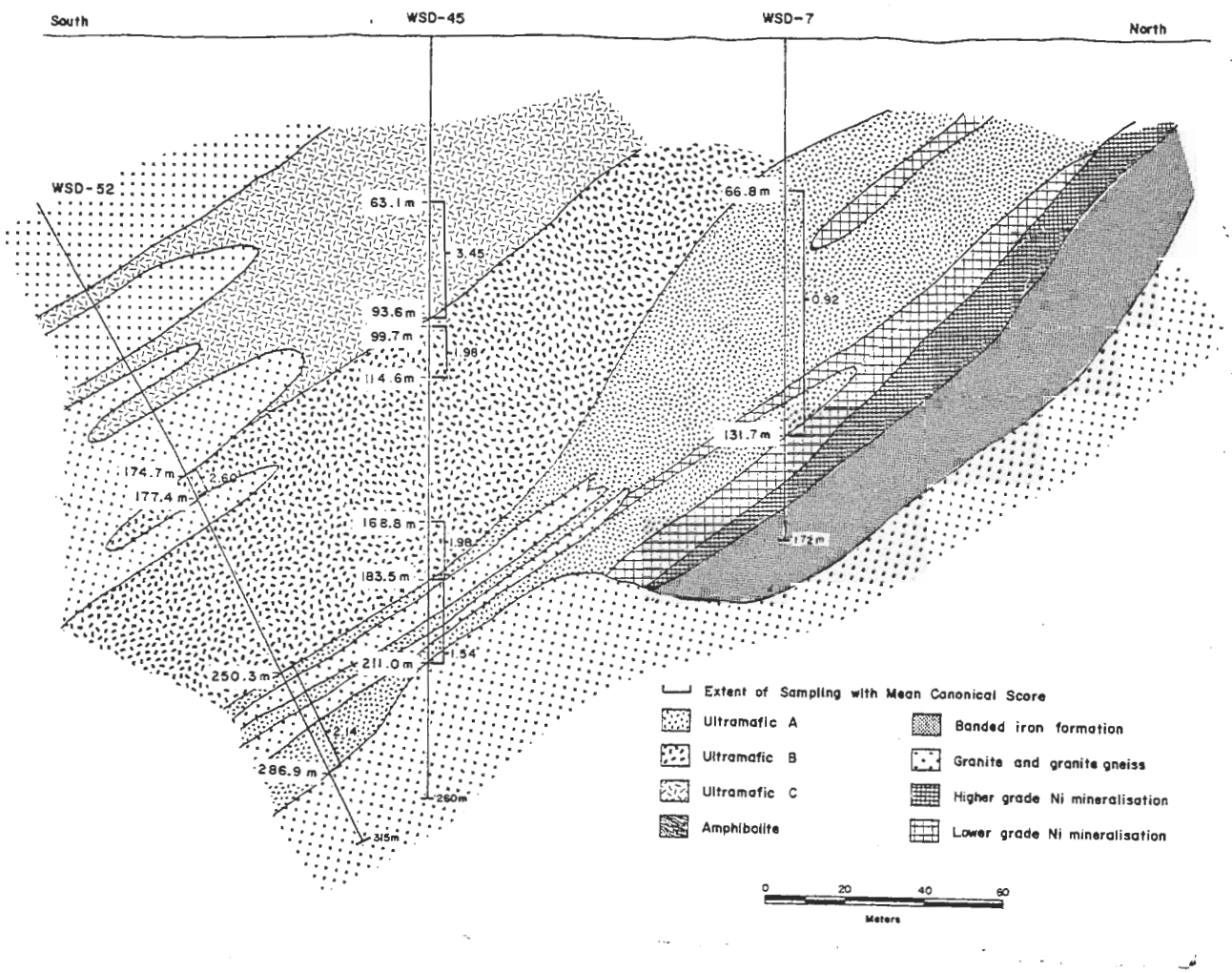

Fig. 18. Cross section E, Windarra South, showing holes 7, 45 and 52, interpreted geology and mean canonical scores for each ultramafic unit.

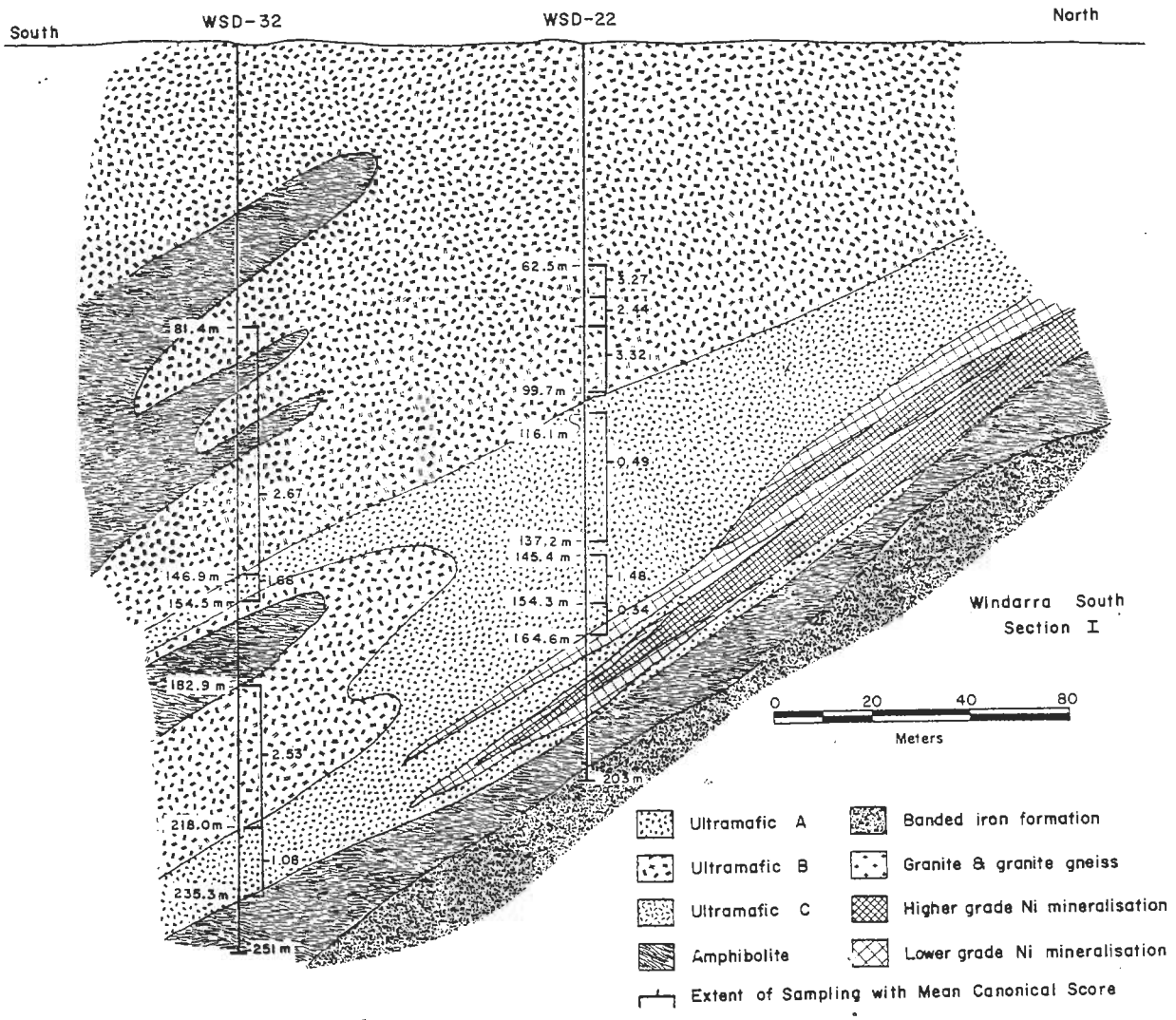

Fig. 19. Cross section I, Windarra South showing holes 22 and 32, interpreted geology and mean canonical scores for each ultramafic unit.

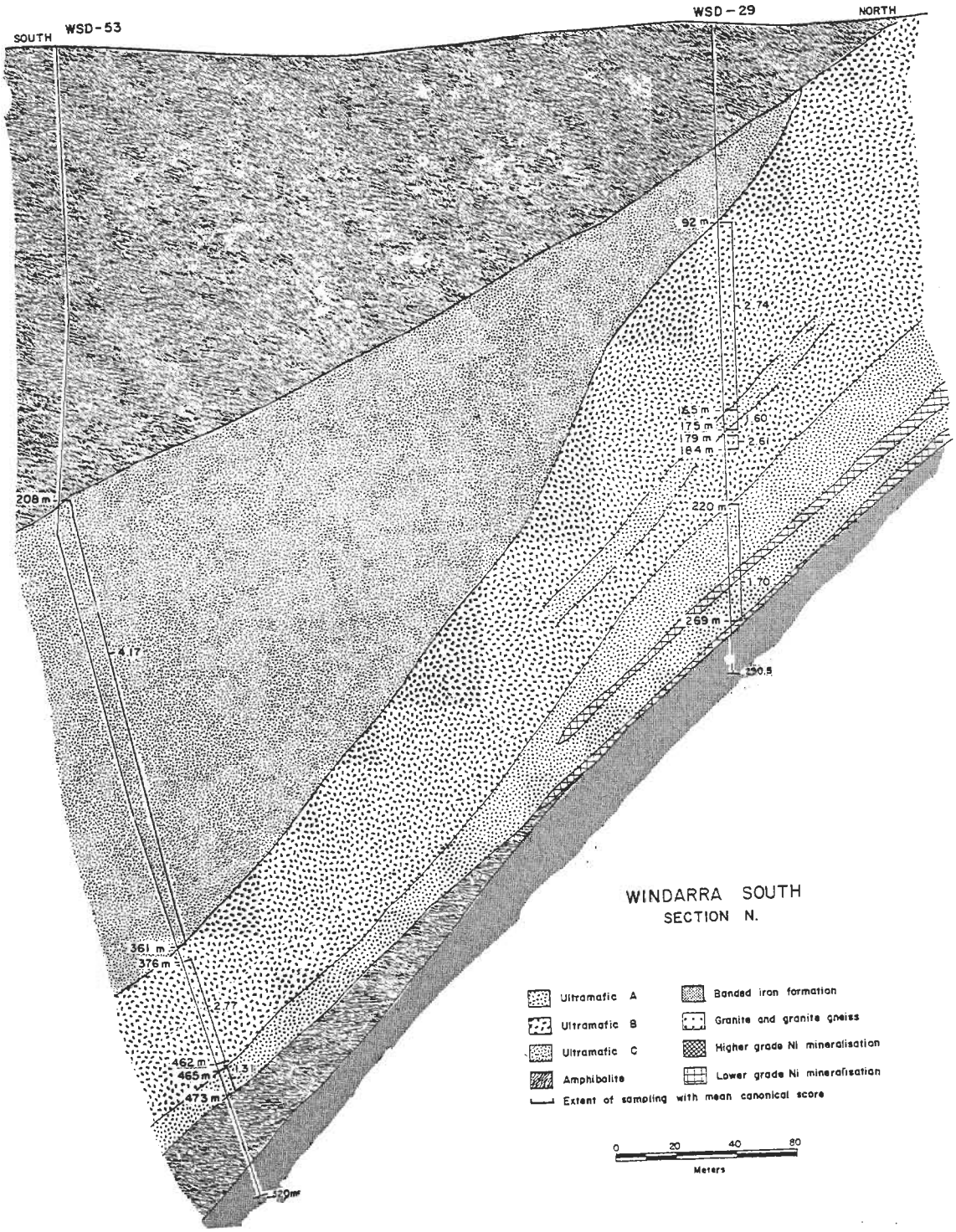

Fig. 20. Cross Section N, Windarra South showing holes 29 and 53, interpreted geology and mean canonical scores for each ultramafic unit.

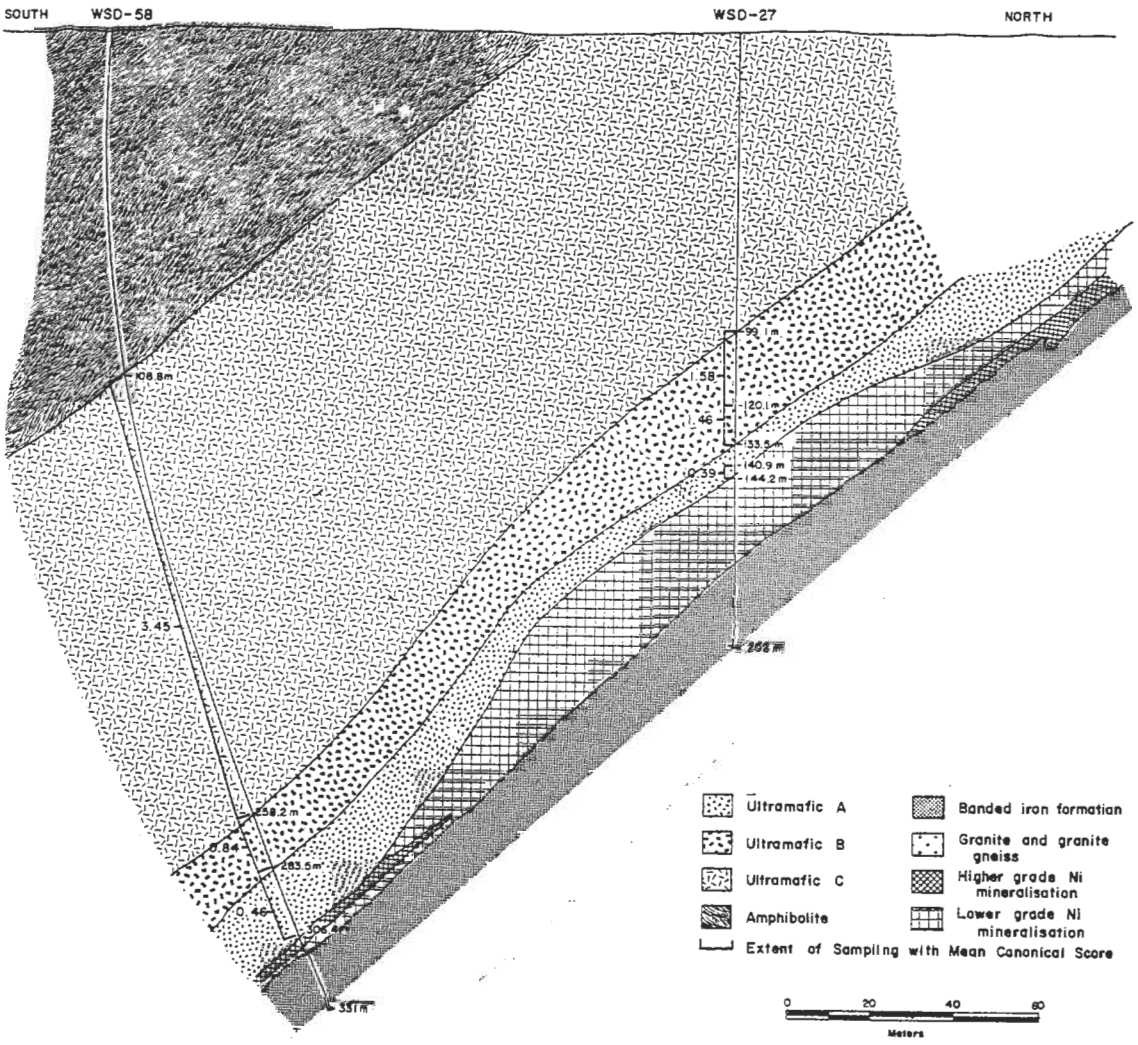

Fig. 21. Cross Section S, Windarra South showing holes 27 and 58, interpreted geology and mean canonical scores for each ultramafic unit.

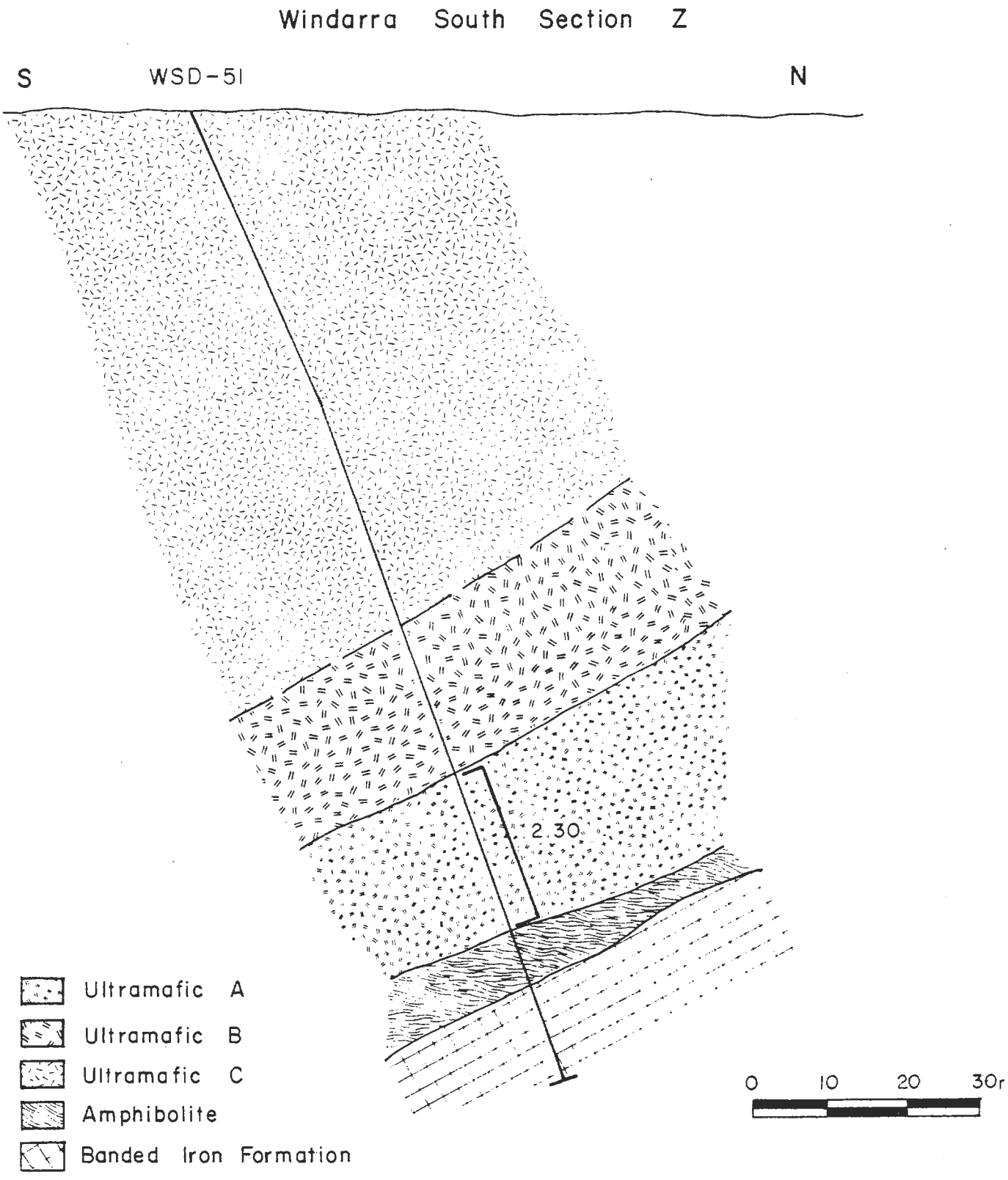

Fig. 22 . Cross Section Z, Windarra South showing hole 51, interpreted geology and mean canonical scores for each ultramafic unit.

dip and at depth, did not encounter ore grade nickel sulphides. Hole WSD 51 on Section Z (Fig. 22), east along strike from the orebody, did not intersect mineralization. Almost all samples were assay pulps representing a specific drill core intersection, usually of length one to five feet. Drill hole samples and number of samples taken are given below:

Section	E	E	E	I	I	N	N	S	S	Z
Hole #	52	45	7	32	22	53	29	58	27	51
# of Samples	14	13	16	24	76	30	35	28	16	20

The mean chemical values for Windarra South ultramafics are given in Tables 3 and 8. Nickel and iron are slightly less than the mean for all mineralized ultramafics and most of the other determinations are slightly greater than the mean. Magnesium is significantly lower than the mean and reflects the thin unit component of the section. In this respect Windarra South is similar to Kambalda.

Chemically the Windarra South komatiites have been divided into three groups (Table 8 and Figs. 18 to 22). Unit A has a relatively distinct boundary with the overlying unit B and consists of one to four individual komatiites. It can be distinguished by high Ni/Cr ratios and low Ni/NiP ratios. Mean Ni and Cr values are 2737 ppm and 1576 respectively. The relatively high values for NiP and CoP indicate that sulphur has been available to the magma. Mg content (17.7%) is higher than units B and C but is lower than comparable ultramafics in the Kalgoorlie-Norseman Nickel Province. If the Mg is recalculated on an anhydrous basis these ultramafics can be classified as peridotites. Manganese 1047 ppm, is lower than in either units B or C.

Unit A (e.g. 116 to 167 m - Fig. 23; - 465 to 473 m - Fig. 26) the ore host, is genetically related to the sulphide mineralization and reaches its maximum thickness immediately above nickel sulphides. It thins to the east and with depth and its chemical character changes with a decrease in nickel

content and increase in Ni/NiP ratios and chromium. The canonical score for unit A on Fig. 22 east of the orebodies is 2.30, whereas the average score for unit A is 1.18. Similar changes are noted with depth in Fig. 55.

Unit B (e.g. 375 to 462 m - Fig. 26; 62 to 97 m - Fig. 23) is a sequence of lower Ni and Mg rich komatiites which vary from a few tens of meters to 100 m thick. They appear to be intermediate in composition between the ore host ultramafics and unit C, which is a sequence of thin units. Mean nickel content is 1278 ppm, NiP is 517 ppm, Cr is 1693 ppm and Mn is 1275 ppm. Mean canonical score for this unit is 2.60, which is on the boundary between Mineralized and Barren. The range of canonical scores is quite large and many samples from this unit are well within the mineralized group. Individual komatiites, as far as can be determined, appear to be relatively thin and range in width from 3 to 30 m.

Unit C (e.g. 106 to 258 m - Fig 27; 280 to 361 m - Fig. 26) is a sequence of ultramafic lavas similar to the "thin units" at Kambalda (Table 7) and to the ultramafic lavas described by Barnes et al. (1974) from Mt. Clifford (Fig. 10). Nickel, NiP and Mg values are lower than in units A and B, and Cr is considerably higher. Insufficient data is available to determine the thickness of individual komatiites. Canonical scores for this unit are all within the Barren komatiite range.

Complete geochemical results for hole 22 (Section I) are shown in Table 9 and in Fig. 23. The komatiite sequence was sampled using assay pulps representing composite core lengths of 0.61 to 1.52 m. The komatiites include sections from units A and B, which in this hole can be subdivided into at least five separate komatiites within unit B and four within unit A. Basal contacts are interpreted at 73.2, 76.5, 81.1, 94.5, 99.7, 119.8, 137.2, 154.3 and 167.7 m. Unit A, the ore host, although interpreted as consisting of four komatiites is separated into two parts by the presence of disseminated nickel sulphides at a depth of 137.2 m. Alternatively, unit A could be interpreted as consisting

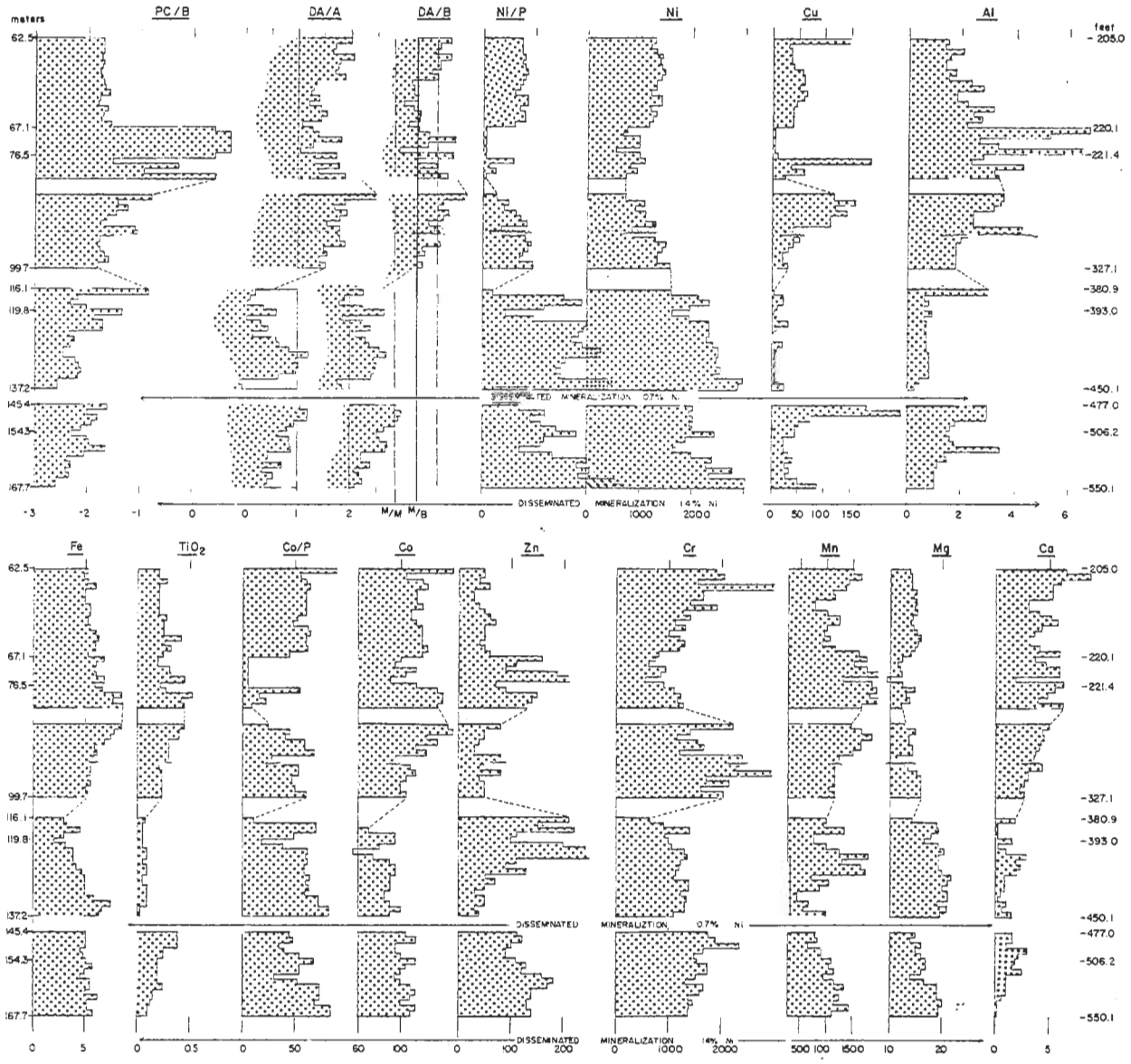

Fig. 23. Histograms of geochemical results, discriminant analysis B scores and principal component B scores for hole 22, Windarra South. Vertical dimension is not to scale. M/M and M/B indicate the mean values for mineralized and barren komatiites respectively. Note the general increase in NiP, Ni and Mg towards the base of the entire sequence whereas Mn and Ca decrease. Al, Cu, Fe and Cr tend towards maximum values in the center of Unit B. Co and Ni have a low correlation, with Co showing a slight tendency to decrease towards the base of the sequence.

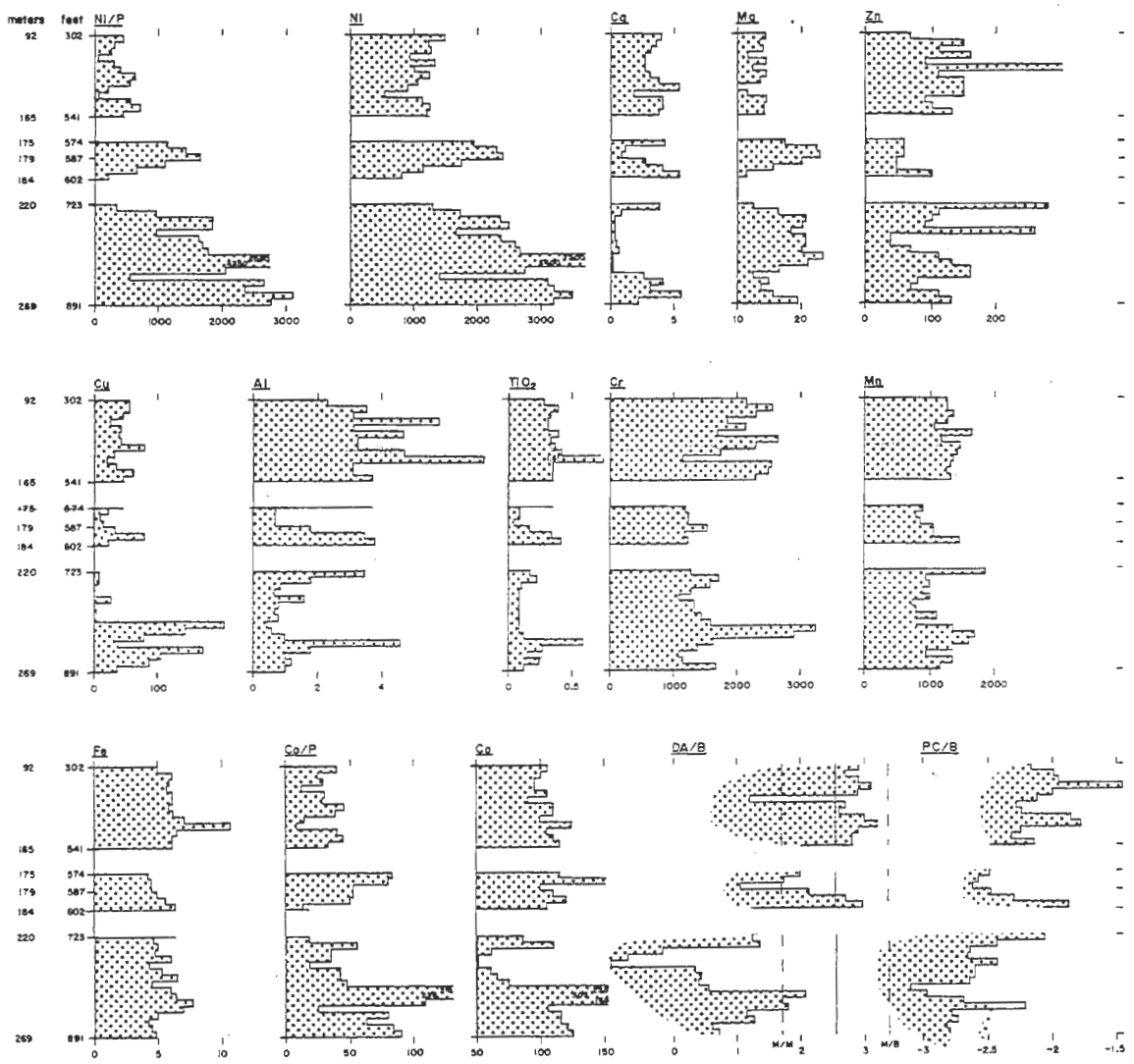

Fig. 24. Histograms of geochemical results, discriminant analysis and principal component scores for hole 29, Windarra South. Vertical dimension is not to scale. M/M and M/B indicate the mean canonical scores for mineralized and barren komatiites respectively. Analyses between 92 and 184 represent Unit B and between 220 and 269 represent Unit A.

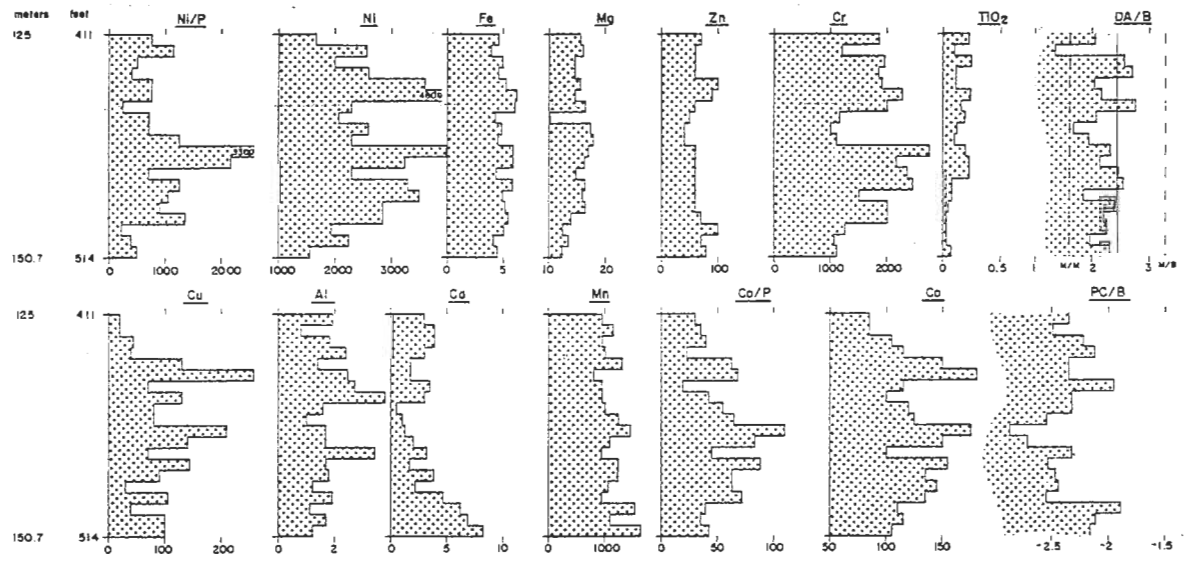

Fig.25 . Histograms of geochemical results, discriminant analysis B scores and principal component B scores for hole 51, Windarra South. Vertical dimension is not to scale. M/M and M/B indicate the mean canonical scores for mineralized and barren komatiites respectively. These analyses represent Unit A, along strike from nickel sulphide mineralization.

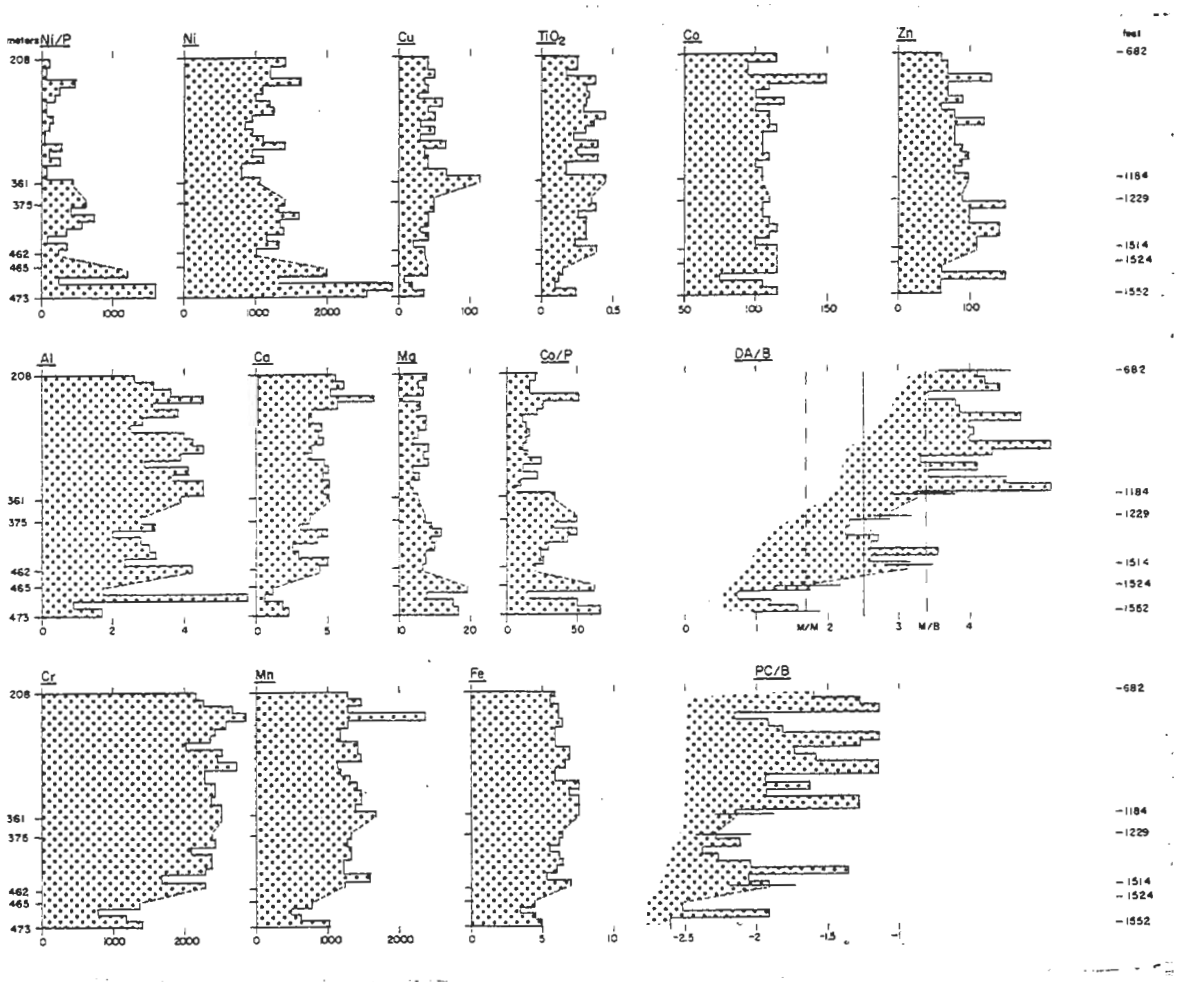

Fig. 26 . Histograms of geochemical results, discriminant analysis B scores and principal component B scores for hole 53, Windarra South. Vertical dimension is not to scale. M/M and M/B indicate the mean canonical scores for mineralized and barren komatiites respectively. These analyses represent Unit A (465-473 m), Unit B (375-462 m) and Unit C (204-361 m), approximately 80 m downdip from sulphide mineralization in Unit A.

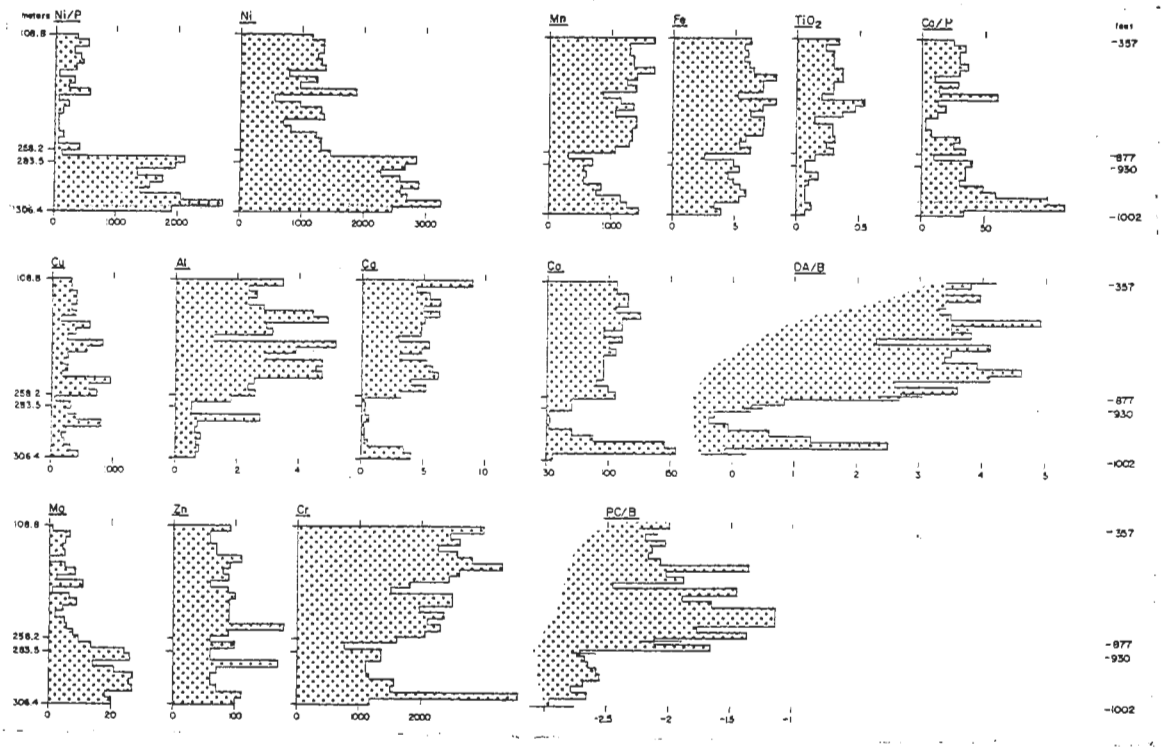

Fig. 27. Histograms for geochemical results, discriminant analysis B scores and principal component B scores for hole 58, Windarra South. Vertical dimension is not to scale. M/M and M/B indicate the mean canonical scores for mineralized and barren komatiites respectively. These analyses represent Unit A (306-283 m) and Unit C (258-108 m). All determinations except Cu and Zn show substantial differences between these units.

of only two komatiites. Komatiites less than 3 m thick would not have been detected. Feldspar porphyry dykes occur at 81.1 and 137.2 m and were intruded at internal ultramafic contacts. Principal component analysis scores reflect the individual komatiites (Fig. 23-PC/B).

Over the whole sequence NiP, Ni and Mg tend to increase towards the basal komatiite whereas Ca tends to decrease. Other elements exhibit definite patterns within parts of the sequence. The ore host komatiite (unit A) is separated into two parts by disseminated mineralization; the upper komatiite is lower in Cu, Al, TiO_2, Co, Cr, higher in Mg and Ni and has a higher mineralization coefficient than the lower section. However, the lower komatiites contain the higher grade sulphides. Values for Ni generally follow the NiP and Mg histograms indicating that nickel as sulphides and nickel contained in the olivine lattice are in equilibrium. An exception is a komatiite unit at a depth of 73.2 to 76.5 m which apparently contained no sulphur. The nickel content of the upper komatiite unit which contains 0.7% nickel as sulphide mineralization, is higher than the nickel content of the lower komatiite which contains 1.4% nickel sulphide mineralization at its base. This could be interpreted to mean that the nickel in the disseminated sulphides at the base of each unit is dervied from the komatiite immediately above and that significant depletion of nickel has occurred within the lower komatiite.

Histograms of geochemical results for holes 29 and 53 (Section N) are shown in Figs. 24 and 26. Samples are widely spaced, preventing detailed interpretation of the section, but the main subdivisions (units A, B and C) are well defined. The ore host includes at least two separate komatiites. As in hole 22, Ni and NiP increase with depth, and Mg is lower in the basal ore host (thick unit) komatiite than in the upper ore host (thick unit) komatiite. The upper unit also has a higher mineralization coefficient than the lower unit (see DA/B, Fig. 24). The ore host thins rapidly with depth and in hole 53 (Fig. 20) is only 12 m thick.

Histograms of geochemical results for hole 58 (Fig. 27) show an abrupt increase in NiP and Ni and a less sharp increase for Mg at the top of the ore host unit (see also Fig. 20). Note the drop in Co at the top of the ore host unit. A similar but less accentuated decrease in Co values occurs in holes 29, 53 and 22. Unit B in Fig. 27 has a low canonical score (or high mineralization coefficient) and could be interpreted as part of unit A. It was included in unit B because of relatively low Ni and Mg values. A histogram of geochemical results for hole 51 (Section Z) is included as Fig. 25 for comparison with ore host komatiites in the mineralized zone. Hole 51 is east of the main sulphide mineralization and has relatively high Ni/Nip ratios and low Ni/Cr ratios suggesting that there may be chemical gradients in the ore host komatiite along strike from sulphide mineralization.

4.1.3 Trough Wells

Trough Wells is a small nickel sulphide occurrence in a volcanic komatiite sequence near the northern extremity of the Southern Cross greenstone belt (Fig. 28). It is within the central part of the Southern Cross subprovince as described by Gee (1975).

The stratigraphic sequence from east to west is as follows (Fig. 29):

1. Granite and granite gneiss, which form the eastern boundary of the greenstone belt.
2. Amphibolites, probably after mafic lavas, which have been extensively intruded and metamorphosed by granitic rocks. The thickness of this unit ranges from zero to several hundred meters at Trough Wells.
3. The third unit, which overlies the amphibolites, is a complex komatiite sequence, dominated by, or almost entirely composed of extrusive, thin flows. This sequence contains massive and disseminated nickel sulphides near the base and within the sequence. It varies up to 200 m in thickness.

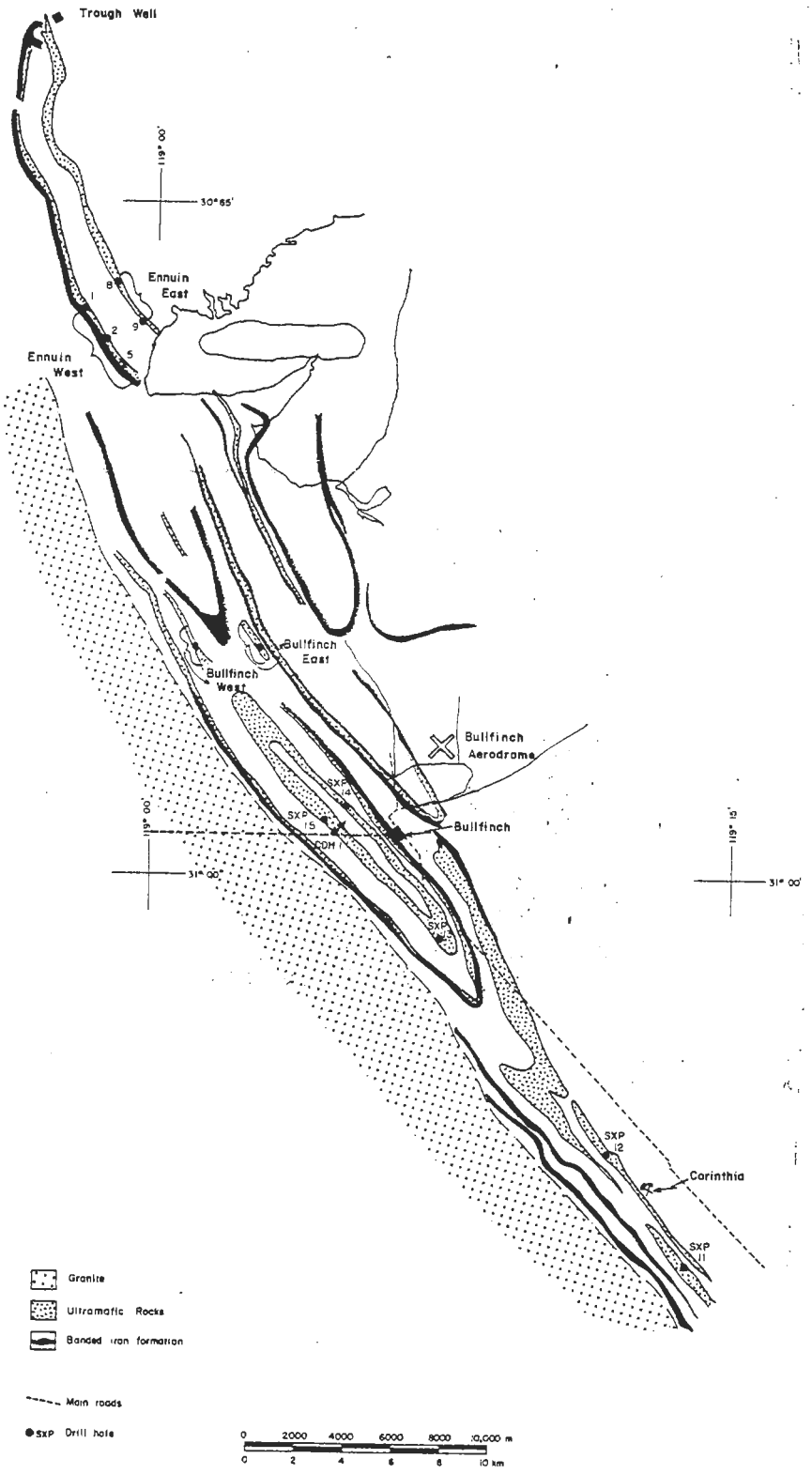

Fig. 28. Interpretive partial geological plan of the northern part of the Southern Cross greenstone belt showing ultramafic sequences, banded iron formations and location of areas sampled.

4. Overlying the komatiites is a thick sequence of mafic volcanics with minor amphibolite. This sequence contains a few narrow banded iron or sulphide rich sediment lenses, has been intruded by granitic dykes and is terminated to the south by granite.
5. Overlying unit 4 is a second ultramafic sequence which varies from 120 to 300 m in width. Little is known of this sequence, but it does contain intercalated mafic and sulphide sediment horizons. It has been mapped mainly as serpentinite.
6. Additional mafic rocks overly sequence 5, although highly contorted banded iron formation appears to overlay it to the northwest, and is present within the mafic rocks.

Unit 2, the sulphide bearing komatiite sequence is composed essentially of lenticular komatiite lavas, with minor thicker, peridotite units which may be intrusive. Granitic rocks terminate the sequence to the south and its extent to the north is not known. Although holes A and B (Fig. 29) are only 122 m apart, individual komatiite units cannot be correlated between holes. Petrographic study of Trough Wells samples indicated that the ultramafics have standard mineralogy and consist mainly of serpentine-talc-carbonate, and serpentine-chlorite rocks. Original textures are discernible in many places and spinifex rocks are common. Metamorphism is generally of green schist facies, although higher grade assemblages are present in some areas, and may be related in part to the nearby granitic rocks.

The basal ore bearing unit is very narrow in hole A and appears to be unrelated to the overlying komatiites. The main nickel sulphide mineralization at Trough Wells occurs near the southwest end of the komatiite mafic sequence, south of hole A. No data is available on the size or grade of the mineralized area.

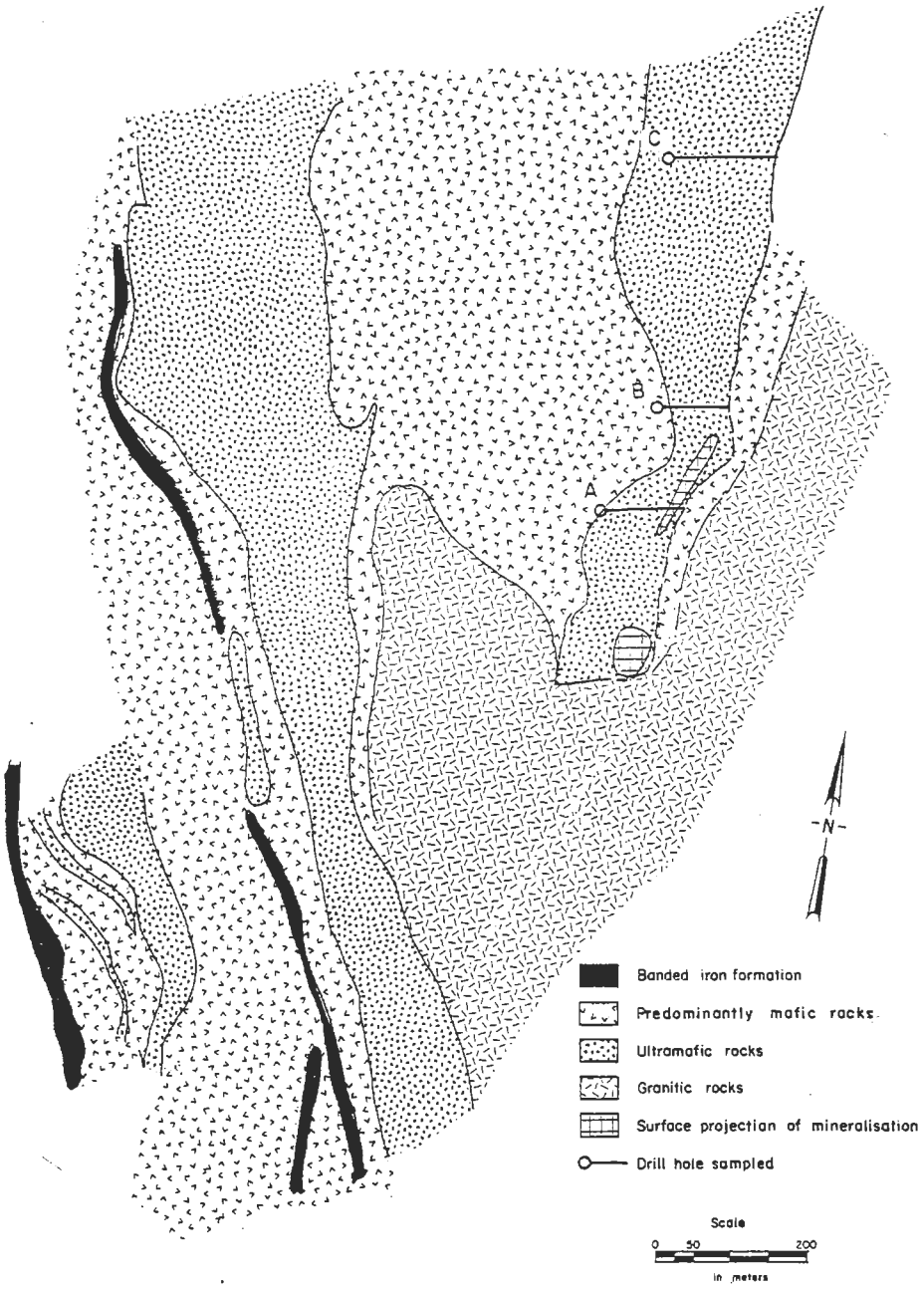

Fig. 29. Interpretive geology of the Trough Wells area showing location of holes sampled.

One hundred and forty-one (141) spot core samples were selected at 3.1 m intervals from three diamond drill holes. The samples represent the entire thickness of the komatiite sequence and approximately 500 m of strike length. None of the holes sampled penetrated the main mineralized zone (south of hole A), but hole A intersected minor sulphides in a komatiite at the basal contact. Discriminant analysis A classified 50%, and analysis B classified 51% of samples as Mineralized. This low correct percentage was caused by the heterogeneous nature of the ultramafic sequence which includes many thin komatiite lavas, similar to those described by Barnes et al (1974). Relatively thick peridotitic and dunitic units occur near the top of the komatiite sequence in holes A and C. Values for Ni and Mg show an overall decrease towards the base of the sequence (Fig. 30), and in this respect Trough Wells differs from most other volcanic komatiite suites, which show a gradation from thicker, more magnesium and nickel rich units at the base, to thinner less ultramafic units at the top. Cu, Zn, Cr and Mn increase toward the base. The western side may be the base of the sequence, but such an interpretation places the sulphide mineralization in the uppermost komatiite unit.

Table 10 shows complete geochemical data for hole A and illustrates the variable nature of the ultramafic. The sequence is essentially low in sulphur, although Ni to NiP ratios are as low as 1.34 and confirm that the Trough Wells sequence contains komatiite units that may host nickel sulphide deposits. However, most of the favorable units are relatively thin and thus likely to contain only small deposits.

4.1.4 Eureka Greenstone Belt

The Eureka Greenstone Belt (Fig. 2) is situated in the extreme northeast of the Wiluna-Norseman Belt (Gee 1975). It encompasses an area some 60 km north to south and 1 to 6 km east to west and includes a number of separate komatiite units. Extensive exploration suggested that nickel sulphides were

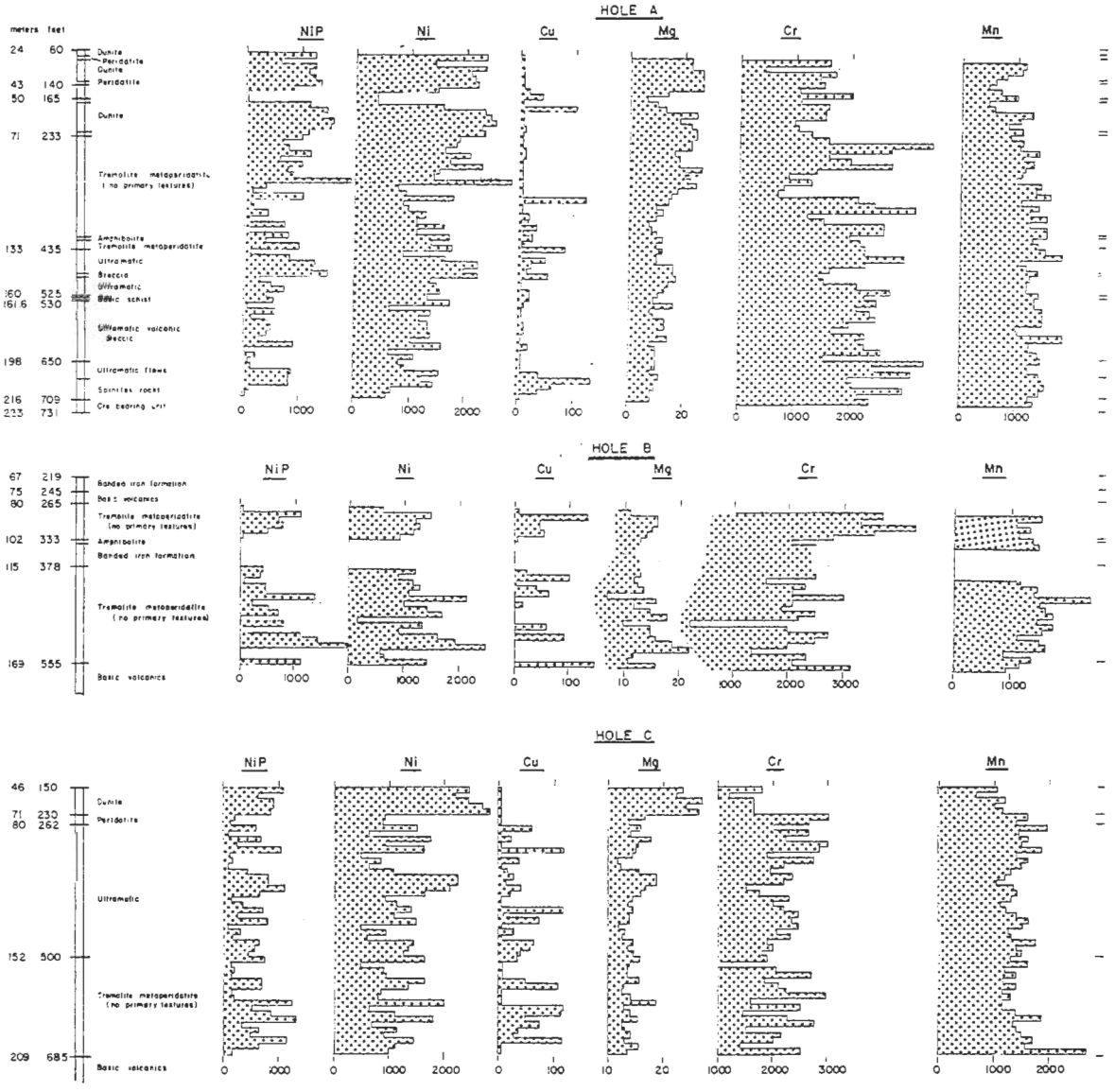

Fig. 30. Histograms of some geochemical results for three drill holes at Tough Well. Vertical dimension not to scale. Note that in holes A and C, Ni and Mg decrease, and Cr and Mn increase towards the bottom of each hole suggesting that the base of the sequence is to the west of the hole collars . Three (each approximately 20 m. thick) thick units can be defined on the basis of the chemical analyses in the uppermost part of hole A.

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co	S	Ni/Cr	Ni/Ni
244	80	1.58	1250	2350	2	4	1.30	0.38	21.00	60	1600	1100	9.90	85	160	0.110	1.47	1.88
	90	0.42	610	1450	2	2	0.50	1.35	21.40	50	450	1050	3.75	30	80	0.040	3.22	2.37
	100	1.66	1260	2350	4	5	1.30	0.85	22.70	60	1700	800	7.10	70	150	0.070	1.38	1.86
	110	0.74	1125	2075	2	4	1.55	0.04	22.70	60	1450	600	7.20	15	80	0.080	1.43	1.84
	120	0.54	1250	2150	2	2	1.90	0.05	22.70	60	1500	500	5.90	37	100	0.090	1.43	1.72
	130	-0.50	1375	2200	2	2	1.05	0.04	23.20	60	1050	700	5.90	15	60	0.070	2.04	1.60
	140	2.87	890	1500	16	16	2.30	7.00	16.80	40	2000	1000	7.00	50	120	0.060	0.75	1.68
	150	5.07	40	400	2	40	7.35	0.40	13.05	90	1100	500	10.70	7	130	0.010	0.36	10.00
	160	4.27	50	375	2	2	5.25	0.53	15.15	80	1600	600	7.60	5	120	0.005	0.23	7.50
	170	ND	1190	1600	96	100	1.90	10.20	16.00	120	1550	1250	7.70	67	130	0.140	1.03	1.34
	180	1.68	1440	2325	2	5	1.30	1.15	22.40	60	1550	1050	6.60	90	140	0.090	1.50	1.61
	190	1.74	1410	2450	2	5	0.70	2.15	18.80	60	1000	850	14.55	130	240	0.060	2.45	1.74
	200	1.58	1600	2525	4	5	1.65	2.15	21.00	60	1100	1100	6.35	123	210	0.080	2.30	1.57
	210	1.30	1490	2300	8	12	1.30	0.95	22.20	60	1300	900	7.20	83	140	0.060	1.77	1.54
	220	2.84	1140	2325	2	4	1.30	2.30	21.70	60	1600	1100	5.65	200	270	0.080	1.45	2.04
	230	2.94	1050	1900	2	5	1.90	2.30	20.70	70	3600	1050	8.30	65	140	0.050	0.53	1.81
	240	2.73	700	1825	4	5	1.80	2.05	21.20	70	2750	1400	9.65	50	160	0.040	0.66	2.60
	250	2.07	765	1575	8	9	2.15	5.05	18.30	60	1600	1100	7.80	45	120	0.050	2.06	2.29
	260	2.03	1200	2100	10	11	2.15	3.00	19.30	60	2000	1300	7.30	53	130	0.080	1.05	1.75
	270	2.43	650	1725	4	5	2.00	3.15	18.80	70	2750	1150	9.10	43	120	0.040	2.65	0.65
	280	1.54	1025	2300	2	5	1.65	1.15	23.00	60	1400	1100	7.80	50	130	0.030	2.24	1.64
	290	0.98	800	1525	2	4	2.15	2.40	20.40	60	900	1000	8.75	33	100	0.030	1.69	1.66
	300	1.23	875	1450	2	5	1.55	0.95	22.70	60	1300	1450	6.90	38	80	0.060	1.11	1.66
	310	0.84	1925	2875	6	7	0.95	0.80	22.70	60	800	1350	7.10	153	210	0.100	3.59	1.49
	320	1.33	400	800	8	9	2.40	4.25	18.65	70	700	1600	6.90	33	90	0.040	1.14	2.00
	330	2.93	175	950	2	2	3.75	5.30	17.50	80	2150	1100	7.70	20	110	0.010	0.44	5.42
	340	2.51	1025	1800	128	122	3.10	3.40	17.00	90	2450	1400	10.00	70	160	0.120	0.73	1.75
	350	3.48	125	875	2	2	3.90	4.00	14.80	100	3200	1250	10.70	20	120	0.010	0.27	7.00
	360	2.43	165	1000	2	2	2.65	5.20	15.60	100	1250	1550	7.80	15	120	0.010	0.80	6.06
	370	2.39	415	1300	20	20	2.90	4.00	15.40	80	1550	1250	7.80	30	120	0.030	0.84	3.13
	380	2.34	100	1125	20	2	4.55	4.25	13.70	100	2650	1550	10.45	13	120	0.005	0.43	11.25
	390	2.61	750	1650	32	31	3.75	4.90	14.65	90	2650	1550	9.30	53	140	0.070	0.62	2.20
	400	3.46	115	1175	6	7	5.10	4.40	15.25	80	2000	1300	8.30	16	140	0.005	0.59	10.20
	410	2.36	825	1750	22	25	2.40	5.25	15.95	90	2200	1400	7.70	50	130	0.060	0.80	2.12
	420	2.51	490	1400	2	4	3.15	3.50	15.10	100	2300	1550	8.75	35	120	0.030	0.61	2.85
	430	2.10	1000	1800	84	85	2.00	6.00	16.10	120	2300	1850	9.10	58	130	0.100	0.78	1.80
	440	3.63	115	900	2	2	3.40	4.10	14.65	90	3000	1100	9.60	18	120	0.005	0.30	7.82
	450	2.45	875	1675	48	49	2.90	4.65	15.40	80	2300	1200	8.30	58	130	0.070	0.73	1.91
	460	1.48	1300	2275	22	21	1.20	4.40	18.40	90	1650	1400	5.80	63	120	0.090	1.38	1.75
	470	1.82	1250	2000	14	16	2.25	3.00	18.00	60	1450	1250	6.35	83	140	0.100	1.38	1.60
	480	1.52	1525	2250	56	62	1.90	3.30	18.65	100	1550	1200	6.45	100	150	0.100	1.45	1.48
	490	2.85	300	1400	6	7	2.40	2.90	17.10	80	2150	1200	7.80	20	120	0.020	0.65	4.67
	500	3.01	500	1500	2	5	2.00	4.40	16.50	80	2750	1400	8.75	40	120	0.030	0.55	3.00
	510	2.29	750	1550	20	20	2.65	5.10	15.25	90	2300	1350	8.20	50	120	0.060	0.67	2.07
	520	2.66	425	1350	20	20	3.15	4.55	14.65	90	2500	1350	9.60	40	120	0.030	0.54	3.18
	530	1.78	575	1750	8	10	2.90	2.30	18.00	110	2150	1500	8.50	45	120	0.040	0.81	3.04
	540	3.41	75	750	2	2	3.50	4.90	14.30	80	2400	1500	9.45	12	90	0.005	0.31	10.00
	550	2.60	575	1400	8	7	2.10	5.20	14.50	90	2500	1500	7.80	40	120	0.040	0.56	2.43
	560	2.80	190	1200	2	2	4.30	3.30	16.60	80	2000	1000	6.35	22	120	0.010	0.60	6.31
	570	2.07	415	1350	10	11	4.10	4.10	16.80	100	1700	1050	6.10	30	110	0.030	0.79	3.25
	580	2.31	490	1375	6	11	1.65	4.00	15.40	100	2300	1850	8.60	30	90	0.040	0.60	2.81
	590	1.78	425	1400	4	5	2.40	3.50	17.10	80	2200	1250	7.45	20	70	0.020	0.64	3.29
	600	2.50	300	1050	2	4	2.55	4.65	14.20	70	2300	1250	7.45	30	70	0.030	0.46	3.50
	610	2.61	925	1600	18	19	2.55	5.30	15.00	80	2600	1400	8.20	57	130	0.100	0.61	1.73
	620	3.75	50	650	2	2	3.00	6.00	14.80	70	1450	1550	5.90	10	100	0.005	0.45	13.00
	630	3.25	215	1100	2	2	4.00	3.80	14.80	80	3400	1250	11.15	25	120	0.020	0.32	5.11
	640	3.68	100	825	2	2	3.75	3.80	15.00	80	2500	1250	9.10	15	120	0.005	0.33	8.25
	650	3.56	150	950	2	2	3.50	4.40	14.20	80	3150	1450	10.80	22	120	0.005	0.30	6.33
	660	2.07	900	1550	40	39	2.30	4.25	16.50	90	2000	1500	7.70	62	120	0.150	0.78	1.72
	670	2.14	825	1250	140	132	2.90	4.90	15.10	130	2100	1550	7.10	55	110	0.090	0.60	1.52
	680	2.80	850	1425	62	62	3.75	5.10	14.80	90	3000	1450	9.10	60	130	0.120	0.48	1.68
	690	3.56	115	700	38	36	3.25	6.20	14.00	80	2200	1250	8.90	17	90	0.020	0.32	6.08
213.4	700	3.84	50	625	2	2	4.00	5.45	14.00	90	2400	1350	8.75	7	90	0.005	0.26	12.50

Table 10. Complete geochemical analyses, canonical scores (B), Ni/Cr and Ni/NiP ratios for komatiite samples from hole A at Trough Wells. Hole A was sampled at 3.1 m. intervals over a hole length of 190 m. The analyses in Table 10 indicate that Trough Wells ultramafic is a heterogeneous, volcanic komatiite sequence. Note that Ni and Mg decrease, and Cr increases towards the basal contact

suggesting that the basal contact is the western contact, not the eastern contact where nickel sulphides are present . The uppermost 60 m. of hole A consists of peridotitic thick units whereas thin units with numerous spinifex zones predominate in the lower two thirds of the hole.

not present and all komatiites were Barren. The komatiites which are generally devoid of primary textures, represent a volcanic suite although some individual and major units could be of mainly intrusive character. The area has particularly severe exploration problems. Except for the northern quarter where some rubbly outcrop is present, the whole greenstone belt is obscured by pediment gravels, thick soils and wind blown sands. Laterite development is extensive and in many areas leaching within the laterite profile over ultramafics has been sufficiently intense to remove all traces of nickel for depths of up to 30 m below surface. Thus, many strike kilometers of ultramafic remain which have not been conclusively explored.

The Eureka Greenstone Belt is wedge-shaped, ranging from less than a kilometer in width at its southeastern extremity to 10 km or more in width near its northern end. It is flanked to both east and west by gneissic granite (Fig. 31). The most prominant feature in the area is a continuous banded iron formation which averages 60 m in thickness, and is present near the eastern boundary of the greenstone belt. To the west of the banded iron formation is a series of intercalated mafic and sedimentary rocks. Several ultramafic sequences are present, concentrated near the western margin of the belt. Little is known of the mafic and sedimentary rocks and the data available on the ultramafic sequences is largely derived from drill holes. Regional metamorphism has effected all rocks within the area and is generally of low to moderate amphibolite facies.

Some samples of komatiite contained sufficient remnant internal structure to be classified as olivine cumulate rocks, originally olivine peridotites or dunites. Present mineralogy is serpentine, serpentine-talc, serpentine-talc-tremolite and serpentine-talc-carbonate. Other samples showed no internal structure and consisted of the assemblage talc-carbonate-chlorite-tremolite in varying amounts. One sample was classified as a chlorite tremolite rock.

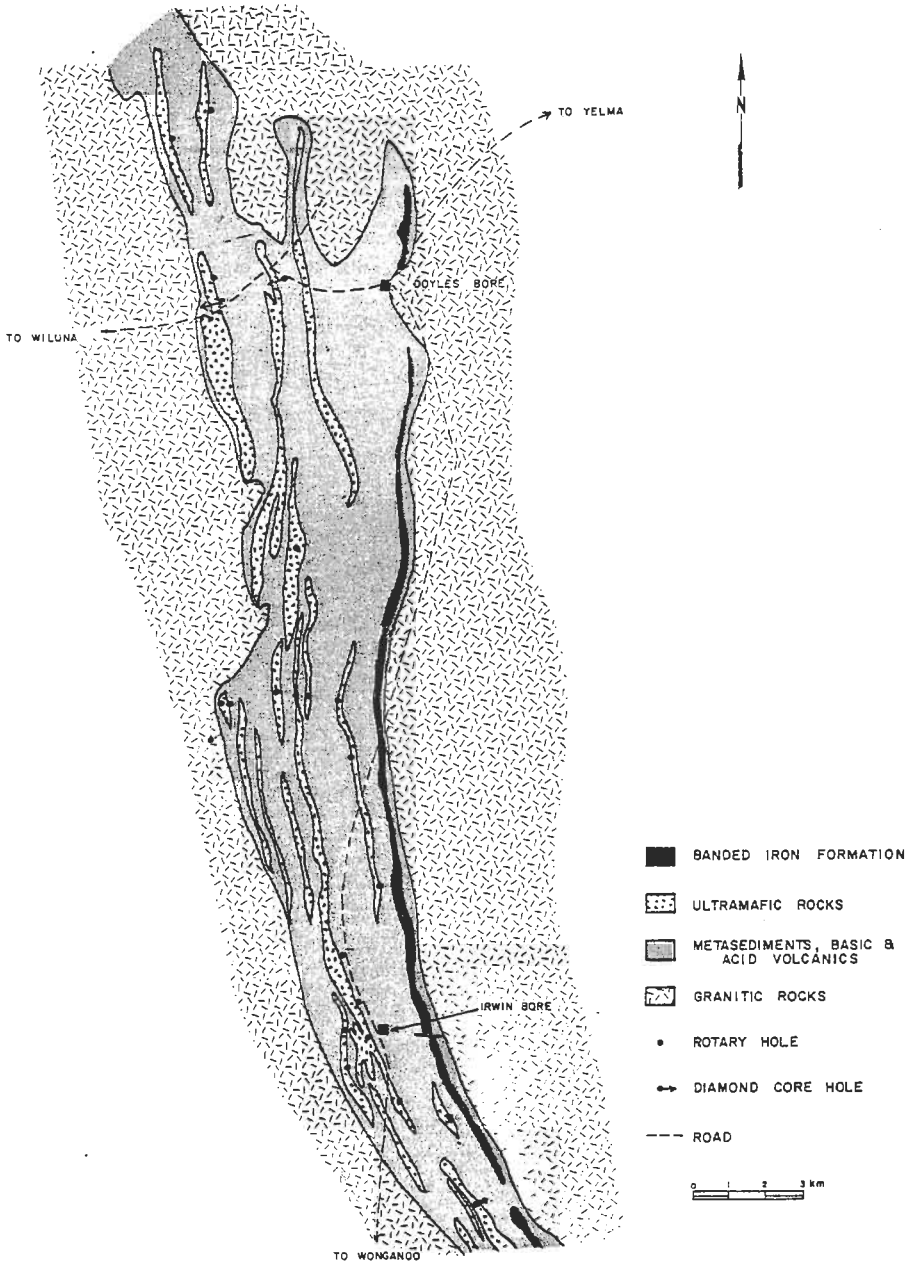

Fig. 31. Interpretive geology of the Eureka Greenstone Belt, showing location of most deep rotary holes.

Hole No.	Sample No.	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	S	Ni/Cr	Ni/NiP
EB 1	1	2.82	450	1675	46	50	2.40	1.40	17.60	60	1800	1000	7.60	0.25	50	150	0.050	0.93	3.72
	2	3.01	400	1700	32	37	1.85	1.80	18.00	50	1800	1000	7.10	0.17	38	140	0.035	0.94	4.25
	3	3.40	390	1700	10	12	1.85	4.55	17.00	50	2150	1050	6.70	0.13	33	140	0.030	0.79	4.36
	4	3.56	825	2025	140	150	1.75	4.10	17.20	40	1950	950	6.05	0.17	88	180	0.120	1.04	2.45
EA 2	1	3.19	275	950	40	48	3.15	2.55	12.70	130	2150	1350	10.20	0.42	45	150	0.095	0.44	3.45
	2	3.13	360	1325	60	57	2.00	0.85	14.45	80	1900	1000	9.35	0.33	50	170	0.050	0.70	3.68
	3	2.89	300	1225	32	37	2.00	1.25	15.70	80	1650	1400	10.10	0.17	40	150	0.030	0.74	4.08
	4	3.30	140	1300	32	38	2.25	0.72	15.30	90	1800	600	9.65	0.25	33	170	0.010	0.72	9.28
	5	3.06	200	1175	34	35	1.75	1.25	15.70	90	1600	1500	10.10	0.25	35	160	0.025	0.73	5.88
	6	2.79	275	1250	48	45	2.10	2.40	14.65	90	1650	1200	10.10	0.25	43	150	0.035	0.76	4.55
EA 1	1	3.53	175	1475	2	5	2.25	2.90	17.20	40	1750	850	6.50	0.20	30	120	0.020	0.84	8.42
	2	3.42	190	1125	26	35	2.10	2.65	14.65	80	1900	1400	9.60	0.25	35	140	0.030	0.59	5.92
	3	3.68	255	1700	10	13	2.00	1.60	18.40	30	2100	900	7.00	0.13	45	140	0.015	0.81	6.66
	4	3.05	190	1800	30	31	2.00	0.49	18.60	40	1500	800	7.10	0.05	28	140	0.010	1.20	9.47
	5	2.37	780	2100	4	7	1.75	1.40	19.25	40	1650	700	5.55	0.17	50	120	0.050	1.27	2.69
	6	3.22	375	1300	38	42	2.40	4.95	14.80	50	1800	1050	5.75	0.13	23	100	0.055	0.72	3.47
	7	2.72	450	1400	32	35	2.25	4.95	15.20	50	1450	1200	5.40	0.17	30	100	0.040	0.97	3.11
	8	2.83	50	1450	24	29	2.50	3.15	15.70	30	700	700	6.80	0.17	15	100	0.005	2.07	29.00
	9	2.77	125	1400	54	69	2.50	7.25	14.65	40	950	1900	6.20	0.17	25	90	0.020	1.47	11.20
	10	4.64	40	1450	24	24	3.80	0.95	15.30	40	2300	600	6.80	0.30	5	120	0.005	0.63	36.25
	11	3.76	50	1700	8	9	2.00	5.75	15.00	20	1350	900	5.10	0.17	35	100	0.120	1.26	34.00
	12	3.54	610	1400	28	29	3.00	3.85	14.45	40	2250	900	6.50	0.25	43	130	0.140	0.62	2.29
	13	2.27	525	1875	8	7	1.35	0.31	18.20	40	1950	600	4.90	0.17	43	100	0.015	0.98	3.57

Table 11. Geochemical results, canonical scores (B), Ni/Cr and Ni/NiP ratios for komatiite samples from three core holes at Eureka.

The Eureka ultramafics are a volcanic komatiite sequence, low in Ni and with moderate Cr, and are probably Barren.

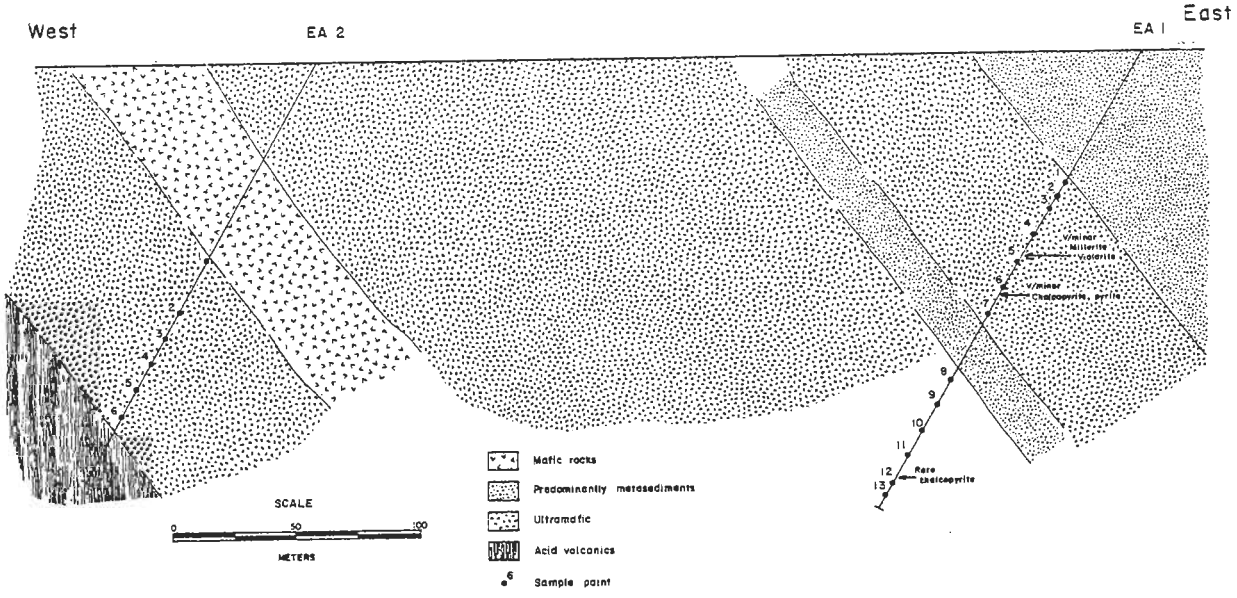

Fig. 32 . Geological cross section through holes EA1 and EA2 at Eureka.

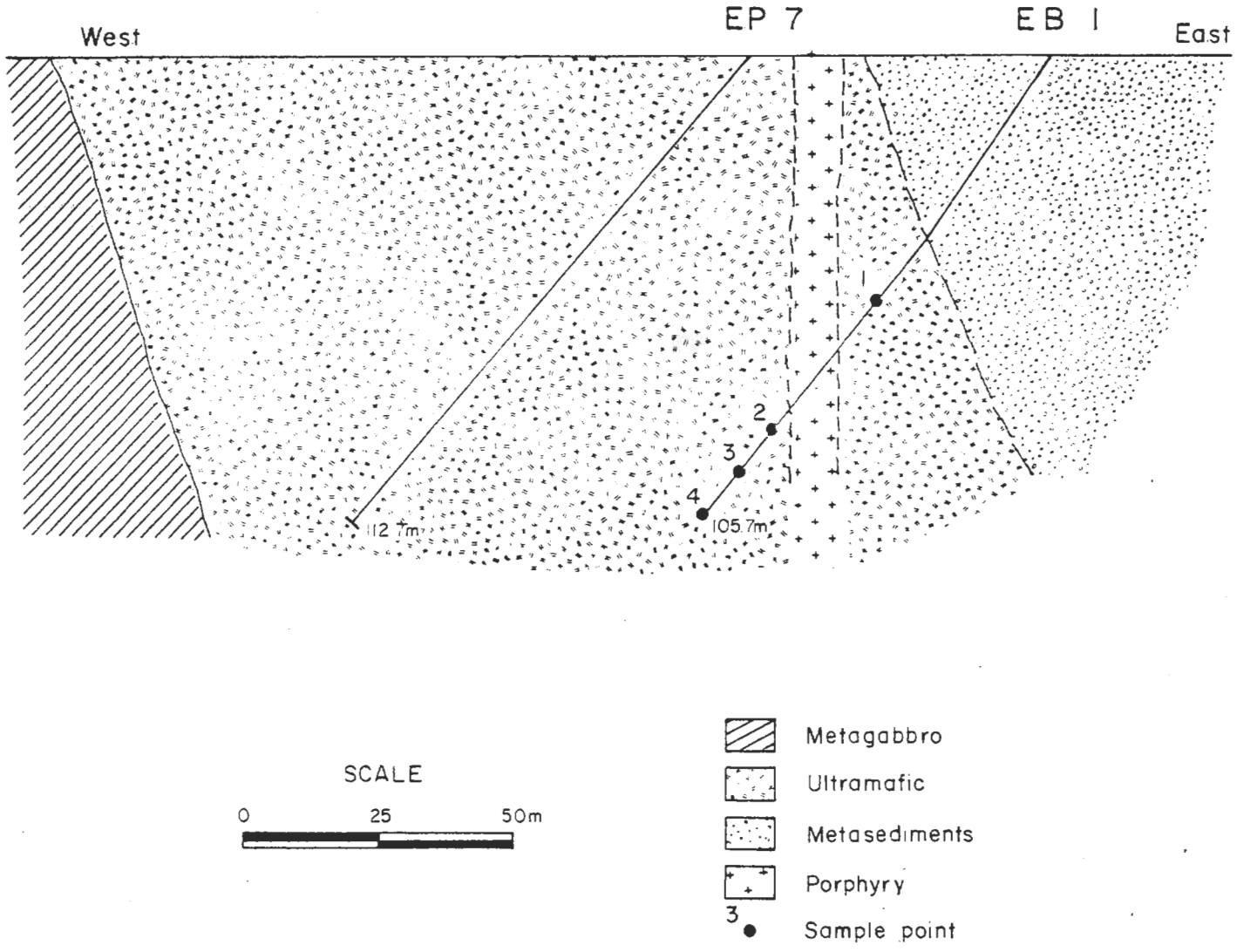

Fig. 33. Geological cross section through hole EB1, Eureka.

Komatiite samples used in the study were obtained from three core drill holes and thirteen rotary holes (Figs. 31 to 33). Two of the core drill holes represent a complete section through one ultramafic sequence (Fig. 32). In addition, samples from some 25 other rotary holes were available with incomplete assay data. Discriminant analysis A classified 64% and analysis B classified 93% of Eureka samples as Barren. Mean chemical values are approximately equivalent to the means for all Barren komatiites with the exception of Cr (1601 ppm) which is considerably lower. A cross section represented by holes EA1 and EA2 through one ultramafic sequence (Fig. 32), indicates that these komatiites are pyroxene peridotites and peridotites. Total nickel and sulphur (represented by both S and NiP) are relatively low (Table 11), but Cr is also in the low to moderate range. The most westerly ultramafic is relatively high in Fe. Hole EB1 (Fig. 33) which sampled a komatiite sequence east of hole EA1 had similar chemistry to hole EA1.

The relatively low chromium content of the Eureka komatiites may indicate that there is a possibility of nickel sulphides somewhere within the greenstone belt. However, the low Ni and NIP and higher Co support a Barren classification.

4.1.5 Red Well

The Red Well (Fig. 2) komatiite sequence is situated in the extreme north-east of the Wiluna-Norseman Belt (Gee, 1975), or in the northern part of the Laverton subprovince (Williams, 1973). It is west and north of the Mistake Creek komatiite (Fig. 34) and forms a linear belt of ultramafic rocks, 35 km in length, within the eastern section of the Banya greenstone belt. It varies from 100 to in excess of 1,000 m in width. The chemistry of the Red Well komatiites suggest that it is a volcanic suite and is Barren.

The Red Well area shows the extreme weathering prevalent in the north-eastern area of the Yilgarn Block. Most of the area corresponds to the upper erosional surface with breakaways leading to the lower erosional surface on

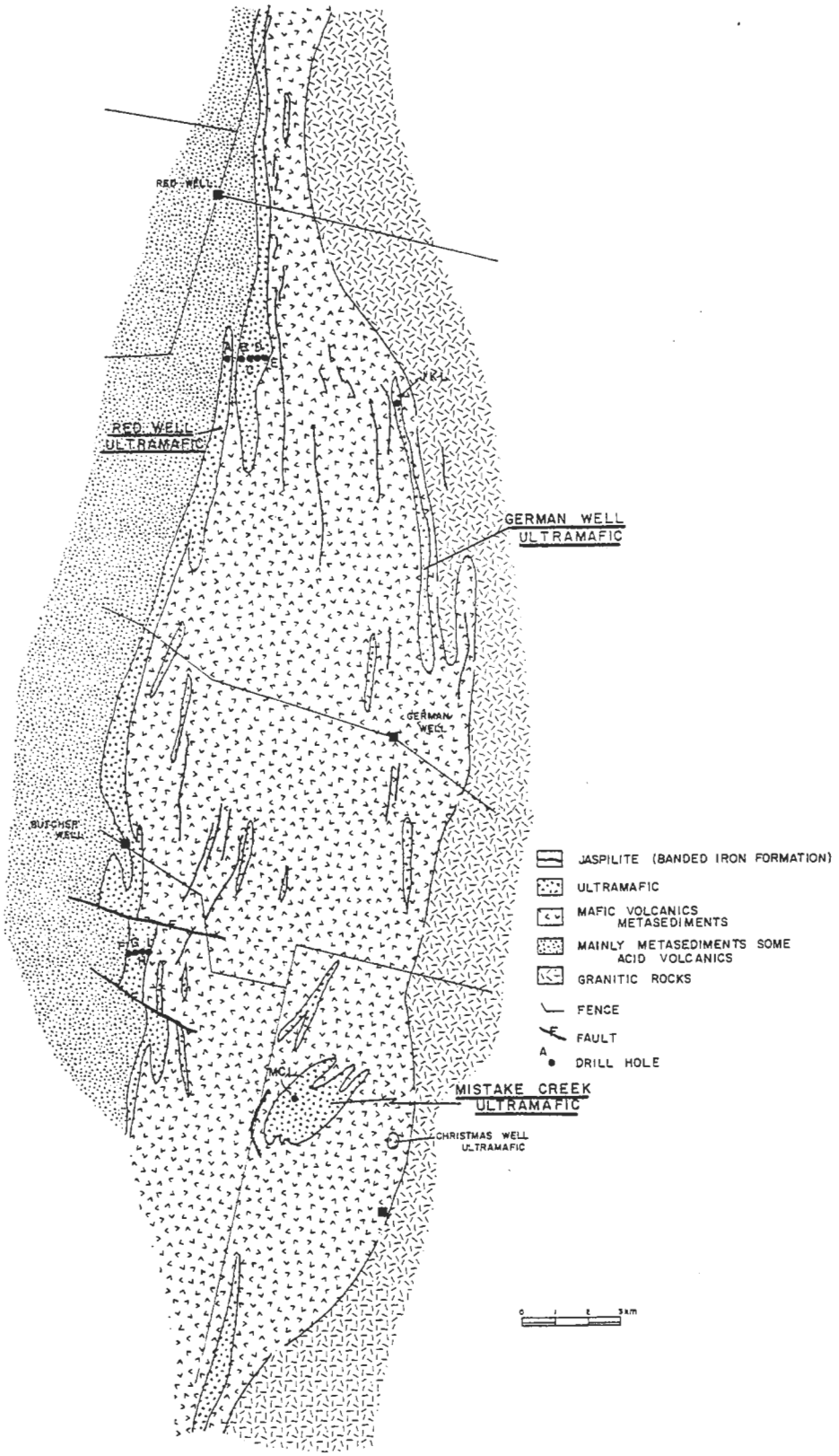

Fig. 34. Interpretive geology of the Red Well, German Well and Mistake Creek areas.

the eastern margin of the area. Outcrop is restricted to a few low ridges of more resistant mafic rock, or thin banded iron formation. The lower lying areas are covered by ironstone gravels derived from laterite. The laterite profile is well developed over most of the area with a thick, leached, pallid zone. The Red Well komatiite sequence does not outcrop and surface evidence of its presence is restricted to a few areas of opaline silica and rare talcose fragments.

The geology was derived from rare outcrops, geochemical drill sample results, rotary drill hole chips and aeromagnetics. The area appears to be dominated by a metasedimentary sequence with less common mafic rocks and numerous thin horizons of sulphide bearing banded iron formation (jaspilite). The metasediments may be partly of acid volcanic derivation and could include acid volcanic extrusive rocks. Ferruginous laterite cap rock (massive limonite) is present in several areas. The Red Well area has been extensively prospected and no evidence of nickel sulphides was detected.

No petrographic descriptions of the komatiites are available but drill cuttings were logged mainly as talc-carbonate-chlorite, talc schist, talc-chlorite-tremolite, chlorite-tremolite and relatively rare serpentinite. Chemically, the ultramafics range from high Mg basalt to olivine peridotite. Peridotites were only intersected in the southernmost part of the area.

One hundred (100) samples were obtained from 53 rotary holes (Table 12). The number of samples per hole varied from one to four and each sample represented a 3.1 m intersection of ultramafic. A few samples which were actually of olivine basalt or high Mg basalt were inadvertently included. Both discriminant analyses classified 99% of the samples as Barren. The samples are low in NiP (average 138 ppm), Ni (average 1282 ppm) and Mg (average 13.8%). Chromium in some holes is relatively low (less than 1500 ppm) but the samples in these cases have been classified Barren on the basis of the low NiP values. The Red Well komatiites are extremely low in sulphur as illustrated by low NiP

Map Code	Hole Location	Depth (feet)	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	S	Ni/Cr	Ni/N
9	A	240-250	3.86	65	1375	26	50	1.45	4.20	15.90	120	2850	1250	6.70	0.03	15	100	ND	0.48	21.1
		250-260	3.91	40	1450	66	110	1.45	2.40	16.40	120	2700	1300	6.70	0.03	13	100	"	0.54	36.2
		260-270	4.45	50	1500	34	100	1.45	2.40	15.20	110	2850	1300	8.10	0.03	13	120	"	0.53	30.0
9	B	170-180	4.92	40	1050	4	30	4.20	3.70	12.00	90	2300	1500	6.60	0.24	8	100	ND	0.46	26.2
		180-190	4.53	25	1075	4	30	4.05	1.04	12.70	100	2100	1300	7.00	0.43	10	100	"	0.51	43.0
		190-200	4.78	25	400	6	40	5.45	3.73	8.10	80	1050	1500	6.70	0.36	10	90	"	ND	N
9	C	170-180	5.00	40	925	6	50	4.05	4.30	12.10	80	2200	1350	7.00	0.30	13	100	ND	ND	N
		180-190	5.28	25	700	9	50	4.75	4.20	10.55	80	2000	1300	7.00	0.33	10	100	"	"	"
		190-200	4.63	65	975	44	50	3.90	4.30	12.70	90	2900	1200	7.00	0.30	15	120	"	"	"
9	D	180-190	ND	25	200	30	50	7.30	5.70	5.20	90	850	1500	7.55		10	90	ND	ND	N
		190-200	"	25	175	40	60	7.20	3.15	4.80	90	600	1200	7.10		10	80	"	"	"
		200-210	"	25	175	40	70	7.75	4.00	4.50	90	800	1500	7.65		10	90	"	"	"
9	E	210-220	3.59	115	800	30	50	2.60	2.80	12.65	110	1150	1450	9.80	0.62	20	160	ND	0.70	6.9
		220-230	3.04	165	850	44	50	2.50	3.85	12.65	100	1250	1600	10.25	0.62	28	140	"	0.68	5.1
		230-240	3.49	150	775	140	140	3.20	3.75	11.60	120	1600	1500	10.60	0.77	25	140	"	0.48	5.1
9	F	240-250	ND	50	2250	2.5	5	0.43	0.11	20.80	20	2100	400	4.60	0.03	10	120	ND	1.07	45.0
		250-260	"	90	2450	2.5	5	0.37	0.23	20.80	20	2300	400	4.45	0.03	10	110	"	1.06	27.2
		260-270	4.55	100	2400	2.5	6	0.33	0.05	20.40	30	2200	300	4.25	0.03	25	110	"	1.09	24.0
9	G	320-330	4.49	65	1350	8	10	1.15	2.75	17.60	30	1450	1700	6.30	0.03	30	130	ND	0.93	20.8
		330-340	4.59	75	1400	5	10	1.15	2.60	17.60	30	1300	1500	6.50	0.07	30	120	"	0.78	18.7
		340-350	5.73	50	1300	3	5	1.00	7.40	11.75	30	2250	1050	5.20	0.03	15	110	"	0.58	26.0
9	H	220-230	4.25	50	2500	3	5	0.34	0.05	20.20	20	800	500	3.10	0.03	8	110	ND	3.15	50.0
		230-240	ND	80	2350	2.5	6	0.18	0.04	20.60	30	600	600	2.55	0.03	8	100	"	3.91	47.0
		240-250	4.01	65	2350	3	15	0.14	0.05	20.20	30	650	600	3.00	0.03	5	110	"	3.61	38.1
9	I	320-330	3.58	150	2250	6	20	0.23	0.21	20.20	40	1500	800	4.90	0.03	20	110	ND	1.50	15.0
		330-340	3.62	140	2500	4	15	0.21	0.17	20.00	40	1300	700	4.60	0.03	23	120	"	1.92	17.9
		340-350	4.12	90	2300	2.5	15	0.22	0.25	20.40	30	1150	750	4.90	0.03	18	110	"	2.00	25.6
10	J	200-210	3.22	850	1550	18	30	2.15	1.75	19.70	60	2600	1500	8.50	0.20	70	160	ND	0.60	1.8
		210-220	2.87	1050	1600	20	30	2.15	0.75	18.40	70	2600	1400	8.80	0.18	73	160	"	0.62	1.5
		220-230	3.13	1175	1550	24	40	1.85	0.75	19.10	70	2600	1550	8.40	0.22	75	170	"	0.60	1.3
10	K	240-250	3.08	1025	1900	9	20	2.40	0.70	18.20	80	2900	1500	9.50	0.16	98	170	ND	0.35	1.8
		250-260	2.93	900	1750	8	20	2.15	0.85	18.70	70	2800	1500	8.40	0.16	78	150	"	0.63	1.9
		260-270	3.60	1075	1700	10	20	1.80	1.05	21.40	60	2850	1500	9.40	0.12	88	150	"	0.60	1.6
10	L	220-230	3.43	550	1550	14	30	1.80	1.70	17.90	90	3450	1750	7.70	0.20	78	150	ND	0.45	2.8
		230-240	3.42	650	1700	13	30	2.15	1.95	18.20	100	3450	2100	8.50	0.21	103	180	"	0.49	2.6
		240-250	ND	750	1600	9	30	2.30	1.50	20.00	90	3650	1500	9.20	0.23	85	160	"	0.44	2.1
8	MCL	240	2.58	400	2250	2	3	0.18	0.09	22.50	30	1150	550	5.00	0.01	23	120	.005	1.95	5.6
		260	1.73	1325	2375	2	2	0.93	0.02	22.50	40	3300	300	3.80	0.13	8	60	.08	0.72	1.7
		280	2.43	780	2225	2	2	0.26	0.19	23.25	30	1450	750	4.90	0.03	18	110	.09	1.53	2.8
		405	2.42	590	2500	2	3	0.27	0.07	23.25	50	1650	500	5.45	0.10	18	130	.08	1.51	4.2
		430	1.86	690	2575	2	2	0.40	0.02	23.10	50	1400	800	5.55	0.02	25	130	.105	1.83	3.7
		460	2.67	740	2450	2	3	0.50	0.36	22.95	40	1450	500	6.05	0.05	23	140	.08	1.68	3.3
		510	3.03	760	2350	2	2	0.47	1.00	22.50	60	3000	300	6.20	0.03	28	150	.07	0.78	3.0
		550	3.33	375	2250	2	2	0.68	3.80	19.70	40	3350	2100	6.05	0.07	13	90	.06	0.67	5.0
		600	2.53	1090	2300	2	2	0.93	1.45	21.00	60	2900	900	5.55	0.10	48	140	.08	0.82	2.1
8	X Well 1	140-200	3.27	700	2650	3	5	0.06	0.10	26.80	30	1050	550	3.85	0.03	40	130	ND	2.52	3.7
	X Well 2	140-200	3.05	650	2650	2.5	5	0.06	0.07	27.05	30	900	500	3.20	0.03	33	120	"	2.94	4.0
	X Well 3	230-240	2.93	900	2600	2.5	5	0.13	0.14	26.80	30	950	500	3.30	0.03	35	120	"	3.05	2.9

Table 12. Shows geochemical results, canonical scores (B), Ni/Cr and Ni/NiP ratios for komatiites from selected holes at Red Well, German Well and Mistake Creek. The table represents only a partial list of the analyses available. The Red Well (9) sequence is volcanic and includes all varieties of the komatiite suite from high Mg Basalt to peridotites. The outstanding feature of this sequence is the very low NiP (S) content of the komatiites and they can be regarded as Barren. The Mistake Creek (8) results indicate that this komatiite is a homogeneous intrusive body. Some NiP and Cr results can be considered moderate but when compared to Forrestania the Cr results are high. Mistake Creek is in a doubtful category with more Barren than Mineralized characteristics. German Well (10) is a narrow komatiite sequence with high Cr and relatively low Ni and is thus considered Barren.

values and low CuP values relative to Cu.

The large number of holes drilled and the very high percentage of samples classified as Barren indicate that this komatiite sequence is unlikely to host nickel sulphide deposits.

4.1.6 Airport and Yilmia

The Airport-Yilmia greenstone belt is a sequence of mafic to ultramafic rocks enclosed by a metasedimentary sequence which extends south-southeasterly from just west of Kalgoorlie Airport to a point south of Yilmia Hill near Lake Lefroy. The Yilmia Hill area is a tightly folded and strike faulted syncline and the Airport-Yilmia succession can be traced northwest from Yilmia Hill to north of Mt. Marion (Fig. 58). Gemuts and Theron (1975), place this sequence of thin unit komatiites, high-Mg basalts and subordinate tholeiites into their Sequence 6 (see Kalgoorlie-Norseman Nickel Province in Appendix 1) which is essentially a younger mafic sequence than that which contains the nickel sulphide mineralization in the Kalgoorlie-Norseman area. Peridotitic or dunitic komatiites are rare and the komatiites can be classified as a low magnesia, volcanic suite. Cherts and sulphide rich sediment horizons are common. The mafic extrusive sequence has been intruded by large, coarse grained, layered and sill-like gabbroic rocks. At Yilmia one such gabbroic sill can be traced along a strike length of 30 km. Williams and Hallberg (1972) suggested that the layered sills (harzburgite through gabbro to granophyric gabbro) are derived from a high-Mg basalt magma (MgO content 15 to 18%) and that they may be comagmatic with the high-Mg basalts of Sequence 6. The geochemical sampling confirms that the komatiites in this belt are low magnesium komatiite lavas which are unlikely to host nickel sulphide mineralization.

Airport includes the ultramafic sequence from the Kalgoorlie Airport, south for 25 km (Fig. 58). Samples were obtained from three diamond drill holes (36 samples) and from a large number of rotary holes (29 samples). Considerable prospecting has been carried out but no significant nickel sulphides have

Hole No.	Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co
A	87.5	287	4.21	21	550	71	76	5.20	5.80	9.30	100	1750	1200	8.20	0.56	25	11
		297	4.46	50	625	13	16	4.95	5.60	9.90	100	1800	1400	8.20	0.50	10	12
		307	4.49	88	625	55	72	4.60	5.50	10.30	90	1800	1250	8.10	0.50	15	12
		312	ND	100	800	690	750	4.00	6.45	11.60	80	2650	1300	8.20	0.50	17	11
		317	4.91	50	725	12	25	4.30	6.10	12.40	100	2600	1350	8.30	0.54	12	11
		327	3.48	50	800	36	43	4.00	5.25	12.40	90	2800	1350	8.30	0.48	10	12
		337	3.96	138	675	52	60	3.20	6.75	12.40	90	2025	1900	8.60	0.40	20	11
		347	3.89	188	875	42	50	3.20	4.30	13.60	100	3100	1550	8.60	0.43	22	12
		357	4.32	50	775	6	20	2.65	4.00	13.20	100	2400	1450	7.40	0.34	10	11
		367	4.62	138	825	28	33	2.90	2.90	14.00	100	2450	1150	8.00	0.40	17	12
		377	4.45	50	950	34	38	3.20	2.10	14.50	90	2700	950	7.70	0.37	12	12
		387	4.54	63	900	8	15	2.65	3.30	14.00	90	2750	1350	8.40	0.40	15	12
		397	4.81	163	925	72	73	2.65	3.30	14.50	80	2500	1200	8.20	0.34	25	12
		407	2.79	100	900	76	73	2.70	2.60	14.50	80	2400	950	8.00	0.30	17	12
		417	5.00	175	975	50	60	2.65	3.00	14.00	80	2850	1200	8.00	0.34	27	13
		427	4.51	25	850	6	10	2.10	1.50	14.90	80	2250	1000	7.40	0.27	10	12
		437	4.39	25	900	2	5	2.40	1.00	14.90	80	2500	750	7.00	0.30	8	12
		447	4.39	175	950	60	73	2.20	3.40	14.00	80	2750	1700	8.20	0.29	33	14
	139.3	457	4.64	288	1025	68	73	2.20	4.60	14.00	80	3100	1950	8.00	0.31	43	13
B	45.7	150-160	3.13	265	1275	22	40	2.70	5.20	14.90	120	1990	1180	7.00	ND	23	12
		160-170	3.69	320	1270	35	54	3.00	5.50	14.90	65	1910	1160	7.10	ND	28	14
		170-180	3.08	335	1310	39	60	2.90	5.00	14.90	75	1910	1230	6.80	ND	32	11
		180-190	2.75	400	1520	30	50	2.70	4.30	16.00	65	1820	1220	6.60	ND	29	10
		190-200	2.89	400	1500	34	44	2.40	4.10	15.60	55	1590	1170	6.60	ND	30	11
		200-210	3.45	260	1305	26	40	2.90	4.60	15.80	85	2480	1220	7.20	ND	27	12
		210-220	1.96	300	1310	35	42	2.40	4.90	12.90	320	2090	1270	6.10	ND	23	10
		220-230	3.35	285	1250	40	42	2.80	3.80	17.20	70	2360	1100	8.10	ND	29	12
		230-240	3.34	320	1340	47	47	2.80	3.60	17.20	67	2420	1050	7.30	ND	28	12
		240-250	3.64	275	1270	29	40	2.80	3.50	17.60	72	2530	1080	6.70	ND	24	12
		250-260	3.64	305	1420	19	35	2.30	4.20	16.70	61	2120	1090	6.20	ND	26	12
		260-270	3.58	420	1380	27	40	2.70	3.90	17.60	64	2470	1120	7.00	ND	30	13
		270-280	4.62	145	1200	15	48	2.80	4.80	16.90	70	2820	1220	7.90	ND	14	12
		280-290	3.98	270	1290	23	48	2.60	4.50	16.70	63	2540	1160	7.00	ND	30	12
		290-300	3.64	315	1250	51	53	2.80	4.60	16.50	64	2410	1140	7.00	ND	23	12
		300-310	4.66	100	1130	35	78	3.10	4.70	16.90	70	2800	1130	7.60	ND	19	13
		310-320	3.73	145	1390	30	54	2.00	4.00	17.80	74	2000	1060	6.70	ND	20	12
		320-320	3.71	230	1370	38	63	2.60	4.40	18.50	60	2160	1100	7.00	ND	28	12
		320-340	3.74	205	1340	39	50	2.40	4.00	17.20	65	2340	1140	6.40	ND	26	12
		340-350	3.59	225	1330	63	72	2.60	4.40	16.90	71	2250	1100	6.60	ND	24	12
		350-360	4.01	205	1230	47	75	2.70	5.60	16.00	66	2450	1290	7.10	ND	28	12
		360-370	4.24	175	1060	35	59	3.20	5.30	15.10	72	2780	1190	7.80	ND	30	13
		370-380	4.08	195	1120	42	54	3.10	5.30	15.50	67	2740	1210	7.70	ND	31	13
		380-390	4.14	145	1220	34	45	2.80	4.30	15.10	67	2530	1090	7.10	ND	22	13
		390-400	4.02	195	1240	37	45	2.20	4.90	15.80	57	2210	1160	7.10	ND	22	13
		400-410	3.59	350	1330	37	50	2.40	4.80	16.40	50	1960	1160	6.50	ND	32	12
	128.1	410-420	3.41	450	1470	20	30	2.30	3.50	16.70	46	1920	940	6.00	ND	34	12

Table 13. Geochemical analyses and canonical scores (B) for samples from a core hole and a rotary hole at Airport. The komatiites are low in Ni and high in Cr indicating that they are likely to be Barren.

been found. Airport was assigned to the Barren group for the statistical analysis and the validity of this assignment is demonstrated by the fact that 92% of samples in discriminant analysis A and 97% of samples in analysis B, were classified as Barren by the discriminant analysis program. The samples form a single population which is characterized by low NiP (189 ppm), Ni (1,030 ppm) and Mg (14.3%) and high Cr (2,337 ppm) and Mn (1,237 ppm)(Table 7). Mean nickel-chromium ratio at 0.4 is low and Ni to NiP ratio at 5.1 is high.

Analyses from two holes are shown in Table 13. The samples from hole A were spot core samples selected at 3.05 m intervals. The entire sequence is low in Ni and Mg and although the samples are too widely spaced to show chemical variations within individual komatiite units, there is little doubt that these ultramafics are a series of thin units. Note that even though it is suggested that the analyses represent many units, there is a definite increase in values for Ni and Mg towards the base of the sequence. Serpentinization and talc carbonate alteration was complete throughout the hole, obliterating all original textures. It may also be important to note that although Mg increases with depth, Fe remains constant. Samples from hole B were rotary drill hole cuttings, bulked in 3.05 m intervals. These samples differ from hole A and contain higher values for NiP, Ni and Mg. They also appear to represent thicker komatiite units and hole B probably intersected between three and five separate komatiites. Down hole thicknesses for these units are of the order of 18 to 30 m but true widths would be approximately 9 to 15 m.

The Yilmia komatiite suite forms the east limb of a faulted synclinal structure (Fig. 35). The rocks can be divided into five main groups: ultramafics, metabasalts, metagabbro, metasediments and granitic rocks. The ultramafics include talc carbonate rocks, tremolite, chlorite rocks, harzburgite and pyroxenite. Serpentinites and peridotites are rare and the ultramafics are a relatively low magnesia, extrusive komatiite lava sequence (thin units). Banded quartzites and pyritic black shales are common and occur as interflow

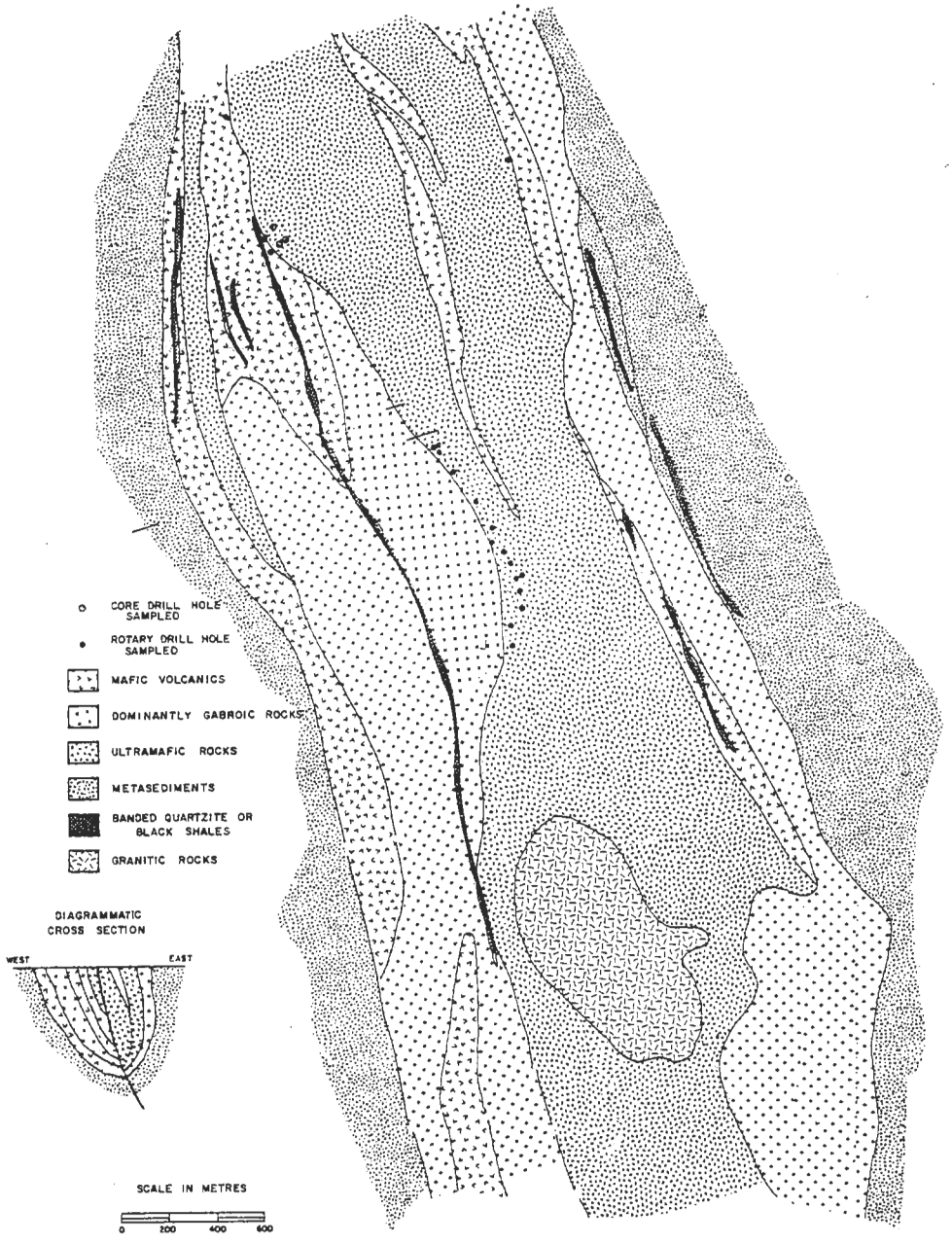

Fig. 35. Generalized geology of the Yilmia area showing location of drill holes sampled.

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co	Ni/Cr	Ni/N
30.5	100-110	3.19	340	1310	72	83	2.50	4.90	18.30	90	2550	1190	6.90	30	116	0.51	3.8
	110-120	3.33	125	1150	42	54	3.70	5.30	18.10	210	3000	1200	7.70	16	129	0.38	9.2
	120-130	2.40	600	1750	32	53	1.90	3.00	20.40	132	2200	970	5.90	35	126	0.80	2.9
	130-140	3.16	390	1500	37	49	2.40	3.70	19.00	80	2440	1000	6.20	28	121	0.61	3.8
	140-150	2.32	610	1640	40	53	2.60	3.90	18.60	144	2280	1000	6.20	40	129	0.72	2.6
	150-160	3.27	345	1430	25	39	2.60	4.60	16.00	89	2300	1040	5.90	30	123	0.62	4.1
	160-170	3.09	230	1160	56	70	2.90	4.80	15.50	175	2600	1050	6.50	24	119	0.45	5.0
	170-180	3.94	200	1200	30	56	2.80	5.00	15.30	82	2500	1230	6.50	22	119	0.48	6.5
	180-190	3.43	290	1300	37	49	2.90	4.70	15.30	93	2530	1180	6.50	33	126	0.51	4.4
	190-200	2.90	300	1300	30	41	3.10	4.80	15.50	155	2500	1170	6.40	32	124	0.52	4.3
	200-210	3.34	285	1200	42	58	3.00	5.40	16.00	110	2370	1200	6.70	29	127	0.51	4.2
	210-220	3.50	320	1290	41	60	3.10	4.60	15.50	80	2480	1170	6.80	28	120	0.52	4.0
	220-230	3.49	450	1340	31	50	3.10	4.30	16.30	71	2700	1080	6.50	39	122	0.50	2.9
	230-240	3.29	380	1310	31	50	3.00	4.50	14.60	113	2590	1100	6.20	31	122	0.51	3.4
76.2	240-250	3.57	275	1220	28	39	3.20	4.90	15.80	82	2600	1160	6.40	28	119	0.47	4.4
73.2	240	ND	365	1090	29	28	6.50	4.20	5.50	100	3840	1180	5.70	37	154	ND	ND
	250	ND	2760	3200	375	416	1.70	10.70	7.10	130	4870	2370	9.00	192	300	0.28	2.99
	260	ND	440	1450	22	344	3.70	15.00	6.20	90	1960	1300	5.80	33	204	0.66	1.16
	270	ND	1250	1450	470	508	3.10	12.20	8.70	125	2800	1530	9.10	236	354	0.74	3.29
	280	ND	160	1160	18	760	3.50	14.30	8.90	115	2600	1660	10.00	36	340	0.52	1.16
	290	ND	1110	1400	470	536	3.30	6.80	11.40	150	2600	1130	9.00	128	240	0.54	1.26
	300	ND	800	1030	119	124	2.30	6.30	15.00	110	1910	1020	5.30	44	88	0.54	1.29
	310	ND	173	940	10	20	4.10	5.90	16.00	85	1760	1000	4.30	13	60	0.53	5.43
	320	3.20	335	950	19	28	5.00	4.90	16.00	110	2760	1060	6.00	19	96	0.34	2.84
	330	3.15	42	950	3	3	2.40	3.50	17.40	160	3380	930	6.10	6	70	0.28	22.60
	340	3.15	159	940	10	20	3.90	4.80	15.80	130	2600	1100	6.30	13	82	0.36	5.91
	350	2.69	318	1220	15	20	3.50	5.90	15.30	150	2270	1340	5.80	18	104	0.54	3.83
	360	2.85	720	1800	26	36	3.20	5.40	15.30	125	3400	1500	6.70	34	122	0.53	2.50
	370	3.28	110	1180	9	14	4.70	4.90	13.70	160	2410	1220	6.00	10	106	0.49	10.72
	380	2.02	650	1400	60	68	4.50	3.70	16.30	240	2750	1590	8.00	37	126	0.51	2.15
	390	2.52	110	1180	8	6	3.80	5.40	15.80	290	2810	1790	7.10	12	116	0.42	10.72
	400	2.22	434	1160	120	122	3.60	7.60	14.90	350	2670	2560	8.10	30	124	0.46	2.67
	410	2.60	313	1140	52	74	4.00	6.80	14.70	230	2310	2190	7.60	25	118	0.49	3.64
	420	2.51	429	1280	115	120	4.30	6.00	13.60	190	2300	1840	7.40	31	122	0.56	2.98
	430	3.29	306	1420	179	212	4.00	4.90	14.90	135	2940	1660	8.40	27	130	0.48	4.64
	440	3.58	91	1170	10	14	3.80	2.20	16.00	105	2470	1080	6.30	11	110	0.47	12.85
	450	2.55	270	1200	39	40	4.90	2.00	16.00	175	2560	1340	6.80	28	120	0.47	4.44
	460	2.54	650	1500	109	116	3.90	1.77	17.50	170	3310	1120	8.20	50	142	0.45	2.30
	470	2.98	319	1460	19	24	4.90	1.36	17.20	110	3010	750	5.70	21	116	0.49	4.58
146.3	480	3.29	400	1370	60	62	3.90	4.80	16.00	125	3610	1070	6.40	23	116	0.38	3.42

Table14 . Representative komatiite results of samples taken from a rotary and a core hole in a volcanic sequence at Yilmia Hill. The canonical scores, Ni and Cr results, all indicate that the komatiites in this area are Barren. The initial 15 m. in the rotary hole represents a peridotitic komatiite, but the low Ni and high Cr suggest that it is Barren. The unusual combination of values in the uppermost 20 m. of the core hole - high NiP, Cu, Co and Ca with very low Mg suggests very substantial alteration of the ultramafic.

beds within all major rock types. The meta-gabbros, harzburgites and pyroxenites represent part of a large intrusive and differentiated mafic complex. Two hundred and forty-six (246) samples were collected from 27 rotary holes and three diamond core holes (Fig. 35). Most rotary hole samples represent a 3.05 m composite sample of ultramafic whereas core samples were spot core samples taken at 3.05 m intervals through the komatiite sequence. The samples are not representative of the whole komatiite sequence but are biased towards a zone along the western margin.

Yilmia was assigned to the Barren group for the statistical analysis. The results indicate that this assumption was correct, with 83% of samples in analysis A and 89% in analysis B being classified Barren. Average geochemical results are similar to those described for Airport and confirm that the komatiite sequence is predominantly a sequence of thin units. The main difference between the two areas is the much higher Zn content at Yilmia.

Complete analytical results for two drill holes are shown in Table 14. In the first hole a 16 m section of peridotite was intersected. It should be noted that although Mg values range from 18.1 to 20.4%, this peridotite has a low total nickel content (1150 ppm to 1750 ppm), and a high chromium content (2200 to 3000 ppm). In addition, the Fe, Mn and Co results are similar to those in the low Mg part of the sequence. These points are indicative of the poor potential of the peridotite as a nickel sulphide host. In the second hole the upper part of the sequence contains relatively high Co, NiP values and high Ni/NiP ratios but very low Mg. This could suggest that the ultramafic is a severely carbonatized peridotite with mineralization potential, but the high Cr results suggest the peridotite is Barren.

4.2 INTRUSIVE KOMATIITE SUITE

The intrusive suite consists of small to large, elliptical, semi-continuous or continuous intrusives of relatively homogeneous peridotite or dunite. Individual bodies range in size up to many kilometers in length and hundreds of meters in width. They may be emplaced as near vertical bodies associated with major lineaments or as sill-like bodies in a wide variety of genetically unrelated host rocks.

Where original textures are still interpretable, they indicate that the intrusives crystallized from a high magnesium parent magma under comparatively low pressure conditions. Equigranular, equant olivine textures are characteristic, whereas spinifex textures are rare or absent. Smaller bodies of this type may be difficult to distinguish mineralogically from thick units of the volcanic suite, especially if they are located close to or within a komatiite lava pile.

Intrusive komatiites are higher in Mg and Ni and lower in Cu, Cr and Mn than volcanic komatiites. Nickel sulphide mineralization tends to be lower grade although individual deposits may be larger. At Perseverance (intrusive), several ore shoots total more than 40 million tonnes at 2% Ni; and at Mt. Keith, several hundred million tonnes of 0.5 to 0.6% Ni in sulphides are present. Sulphides associated with volcanic type deposits have Ni/Cu ratios varying from 8 to 1 to 25 to 1 whereas intrusive associated sulphides vary from 25 to 1 to in excess of 80 to 1. Iron nickel ratios are lower in intrusive suite deposits than in volcanic suite deposits.

Intrusive association komatiites with a high mineralization coefficient have the following approximate chemical values: NiP 1200 ppm; Ni 2500 ppm; Cu 5 to 60 ppm; Al 0.5%; Ca 0.5 to 2%; Mg 20 to 26%; Zn 60 ppm; Cr 1000 ppm; Mn 900 ppm; Fe 6%; CoP 60 ppm and Co 125 ppm. Forrestania hole 4 (Figs. 40 to 42) intersected both Mineralized and Barren komatiites. The barren komatiite

has a mean Mg content in excess of 20% but very low Ni (approximately 1000 ppm) and high Cr (approximately 3000 ppm). Marvel Lock C is a further example of a barren intrusive komatiite. It contains 21% to 22% Mg but only 1750 (average) ppm Ni and 3000-4000 ppm Cr.

Intrusive suite komatiites, whether mineralized or barren, may have substantial sections which are very low in Cu (5 ppm or less), whereas mineralized thick units of the volcanic suite seldom have less than 30 to 40 ppm Cu. The silicate liquid-olivine crystal ratio is lower (i.e. there was less silicate liquid) in intrusive komatiites than in thick units of the volcanic association.

The geochemistry of several intrusive suite komatiites is analysed in detail in the following pages.

4.2.1 Queen Victoria Rocks

Queen Victoria Rocks is a minor nickel occurrence located 51 km southwest of Coolgardie (Fig. 2). The nickel sulphides occur in an irregular northwest trending intrusive komatiite sequence which ranges up to 500 m in thickness. It is surrounded by coarse-grained granite and granite gneisses which contain slivers of metamorphosed sedimentary and volcanic rocks. A laterite cap is well developed and effectively obscures most surface geology. All knowledge of the komatiites has neen gained from drill holes. Nickel sulphides occur as disseminations in various parts of the komatiites. Nickel grades are low and a typical drill intersection would be 30 m of 0.43% Ni.

The greenstone belt, of which Queen Victoria area was once a part, has been almost entirely assimilated by granitic rocks, or metamorphosed to granitic gneisses. It forms the western boundary of the Wiluna-Norseman Belt (Gee 1975) or Kalgoorlie subprovince (Williams 1971), and in contrast to most of the subprovince, contains banded iron formation. Remnants of amphibolites,

metasediments and ultramafic rocks in the form of slivers or discontinuous lenses up to 5 km in length and 1 km in width remain both north and south of Queen Victoria Rocks. The trend of the original greenstone belt was apparently north-south and can be traced for some 70 km to the north.

Coarse-grained granitic rocks occur on the southwestern side of and in places embay the ultramafic sequence. The granitic rocks are essentially granites (mainly potash feldspar with lesser amounts of albite, quartz and biotite) with minor adamellites. Gneissic rocks occur on parts of the komatiite margins and are generally banded and streaked quartz-plagioclase-hornblende-diopside rocks, which may have originally been mafic volcanic rocks. Mafic volcanic and metasedimentary rocks are present on the north-eastern margin of the komatiite sequence. They have been metamorphosed to plagioclase-diopside hornfels and quartz sericite schists. Banded iron formation occurs in the northern part of the area.

The ultramafic consists of multiple intrusive, dunitic komatiite units with some peridotitic phases. Wide zones within the dunitic rocks contain talc and disseminated nickel sulphides. The dunites have not been appreciably effected by metamorphism. Serpentinization is more marked at the outer margins of the complex although even there the original textures are well preserved.

The predominant rock type consists of closely packed euhedral to subhedral olivines partially converted to serpentine. The interstices between the olivine is usually serpentine, talc, spinels, chlorite and sulphide blebs. The peridotitic sections contain coarse orthopyroxenes up to 2 cm in length. Olivine is the dominant mineral, occurs in euhedral to subhedral crystals up to 1.5 cm long and forms at least 90% of most ultramafic rock samples. The olivines are an Mg rich variety, Fo_{90} in composition, with nickel contents of 0.05 to 0.46%. In certain zones the olivines appear to be

depleted in nickel but no relationship was established between nickel depleted zones and internal contacts; the presence or absence of serpentinization; or to the presence or absence of nickel sulphides. Serpentinization effected all major mineral components and is usually a pale yellow or pale green variety, dusted with minute granules of magnetite. Talc and chlorite occur mainly as interstitial components. Chromite occurs as euhedral to subhedral crystals between olivine grains. Some chromites are visibly rimmed with magnetite but all show a gradual enrichment of iron at the expense of chromium, from chromium rich cores to chromium poor margins. The more altered chromites are surrounded and embayed and show depletion of aluminum, magnesium and chromium. Sulphides occur exclusively in interstitial positions, both as discrete blebs and as intergranules with chlorite and magnetite. Total sulphide content is low and probably averages 0.4% or less, increasing to a maximum of 4.5%. Pentlandite is dominant and often the only sulphide. Some pentlandite has been altered to fine-grained millerite and heazlewoodite. Pyrrhotite is relatively rare, indicating that the total sulphur content of komatiites is comparatively low.

The komatiites have not been significantly effected by the surrounding granites, but host sediments and volcanics have been severely metamorphosed. The nickel sulphides are a primary feature and are not genetically related to serpentinization because serpentinization has effected less than 20% of the olivine.

One core drill hole was sampled at 1.52 m intervals through an intersected length of ultramafic of 236 m. A zone of sulphide mineralization with up to 2.0% Ni occurs in the lowermost third of the hole. The drill hole was collared in ultramafic rock and represents approximately half of the total width of the komatiite sequence. Average geochemical results for Queen Victoria Rocks (Table 3) are higher in Ni , Cu and Mg and lower in Cr and Mn

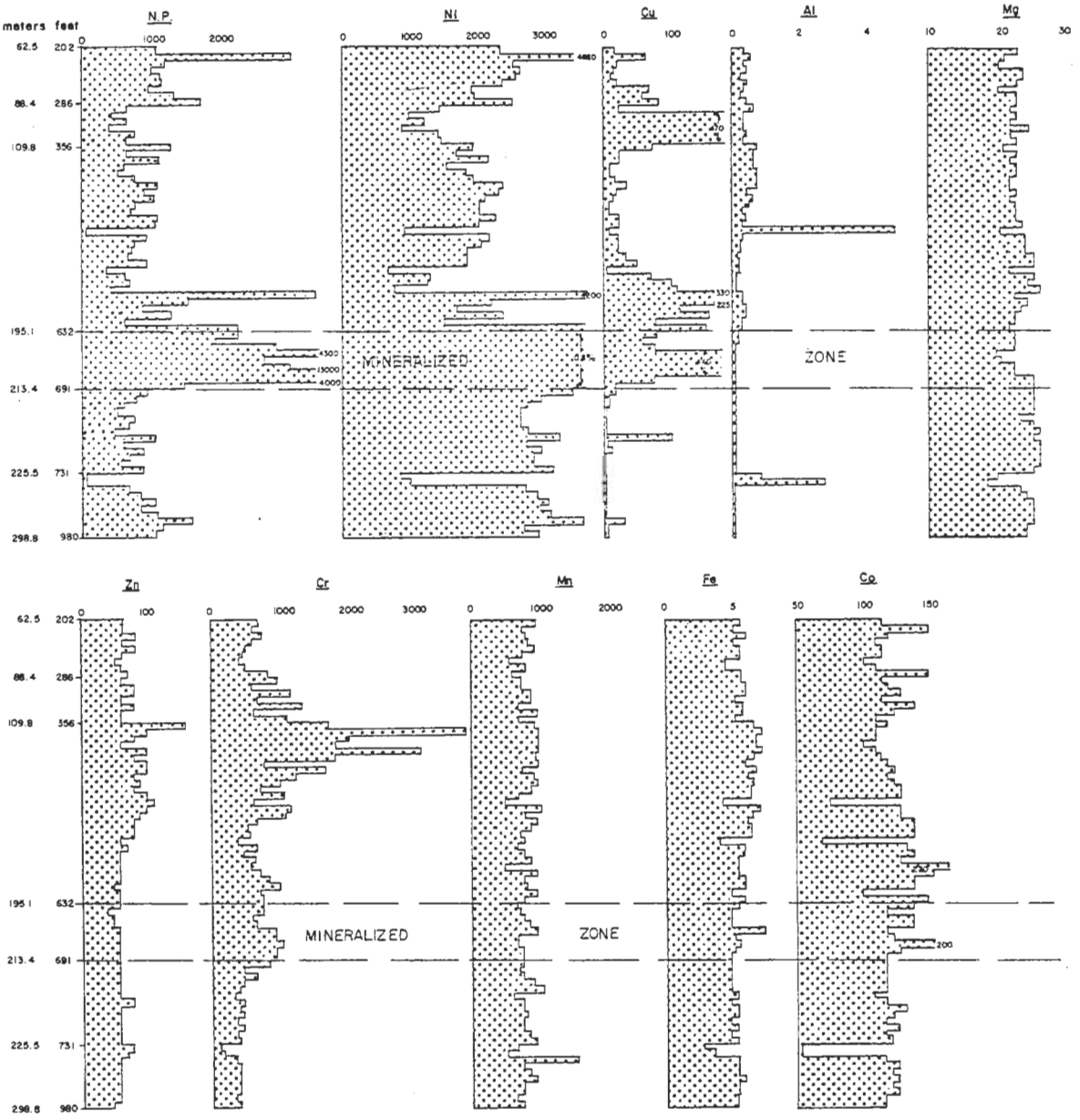

Fig. 36. Histograms of geochemical results for a single drill hole at Queen Victoria Rocks. Vertical dimension not to scale. Main points of note include strong negative correlation between Ni and Cu at a depth of approximately 100 m.; the increase in Cr below 110 m.; and the very low Cu, Al and Cr values below the mineralized zone.

than the mean values for mineralized komatiites. Ni/Cr ratio (Table 4) is extremely high at 3.0, equivalent to Scotia and Forrestania. Discriminant analysis A classified 94% of the samples as mineralized and analysis B classified 100% as mineralized.

Ni and Mg increase with depth and Al, Fe and Cr decrease, suggesting that the hole penetrated from top to bottom of the komatiite sequence (Table 15 and Fig. 36). Discontinuities occur at 88.4 m with an abrupt decrease in Ni and an increase in Cu; at 109.8 m with an increase in Cr and Zn; at 213.4 m which is the base of nickel sulphide mineralization; and at 225.5 m with a decrease in Ni, Mg, Cr, Fe and Co. Other points of note are the negative correlation between Cu and Ni over the interval 88.4 m to 109.8 m; the positive correlation of Ni and Cu between 185 m and 213.4 m; and the zone of nickel sulphides between 195.1 and 213.4 m. The above points, plus a study of the canonical scores in Table 15 suggest that the interval 62.5 to 88.4 m represents a second unit; 213.4 to 225.5 and 225.5 to 298.8 m represent two further units. These units probably do not represent separate intrusions, but can be regarded as either separate pulses within one main intrusive phase or as less viscous components of the magma moving past more viscous or partly crystalline sections of the intrusion. The Queen Victoria Rocks histogram (Fig. 36) shows a strong similarity to histograms for Forrestania holes 4 and 5. This similarity is further emphasized by discriminant analysis D (Fig. 5).

The geochemical results for Queen Victoria Rocks indicate the presence of an extremely favorable komatiite host rock. By analogy to Forrestania, if the komatiites extend north or south of Queen Victoria Rocks, either continuously or as remnant pods and lenses in granite or granite gneiss, there is a high probability that additional nickel sulphide deposits are present.

Depth Meters	Depth Feet	Canonical Score	Nip	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co	Ni/Cr	Ni/NiP
62.5	205	0.74	1138	2400	10	15	0.31	1.05	23.40	60	700	950	5.40	70	115	3.43	2.11
	210	0.01	3200	4800	52	65	0.54	1.05	21.20	60	600	750	4.90	108	150	8.00	1.50
	220	0.62	1275	2575	12	20	0.27	0.90	20.40	80	750	800	5.70	85	120	3.43	2.02
	230	0.50	1050	2700	6	15	0.43	1.25	24.00	60	600	850	5.20	70	110	4.50	2.57
	240	-0.14	1175	2650	6	10	0.24	0.70	24.00	80	500	950	5.50	80	115	5.30	2.26
	250	0.10	1200	2425	10	20	0.38	0.55	22.80	60	450	750	5.50	83	115	5.39	2.02
	260	1.50	988	1975	6	73	0.29	0.70	20.40	50	400	550	4.30	48	100	4.94	2.00
	270	0.70	1375	2000	46	60	0.19	0.75	22.80	60	500	800	4.30	70	110	4.00	1.45
	280	0.98	1800	2600	74	85	0.39	0.75	22.80	70	850	600	5.60	110	150	3.06	1.44
88.4	290	1.63	675	1475	16	23	0.57	0.70	22.30	60	1000	750	5.60	80	115	1.48	2.19
	300	ND	450	1000	600	560	0.33	0.90	22.80	80	600	750	6.00	88	120	1.67	2.22
	310	ND	638	1225	817	805	0.31	1.05	22.30	80	1200	900	6.00	95	130	1.02	1.92
	320	2.46	375	900	202	340	0.31	0.90	25.00	60	700	900	5.20	75	115	1.29	2.60
	330	ND	800	1475	330	408	0.40	0.75	22.80	80	1400	700	5.70	105	140	1.05	1.84
	340	2.35	638	1500	30	255	0.34	0.55	22.80	60	650	1000	5.70	88	125	2.31	2.35
	350	1.48	1325	2000	58	75	0.71	2.10	21.20	60	1150	700	5.20	85	110	1.74	1.51
109.8	360	1.38	738	1725	16	25	0.60	0.75	22.80	160	1800	950	6.70	75	120	0.96	2.34
	370	2.27	1138	2225	16	25	0.65	0.90	21.80	100	3900	1000	6.90	80	110	0.57	1.96
	380	2.07	725	1600	6	10	0.64	1.05	23.40	80	2100	1000	6.30	75	110	0.76	2.20
	390	2.06	550	1900	8	13	0.73	1.05	22.80	60	1900	1000	6.20	50	100	1.00	3.45
	400	2.38	800	2000	8	18	0.65	1.15	21.80	100	3200	1000	6.70	70	110	0.63	2.50
	410	1.52	1150	2450	24	35	0.75	0.85	22.30	80	1900	950	6.20	85	115	1.29	2.13
	420	0.60	950	2375	8	20	0.40	0.70	23.40	100	800	1000	6.00	88	120	2.97	2.50
	430	1.38	1100	2200	8	15	0.61	0.70	22.30	100	1750	750	6.90	93	125	1.26	2.00
	440	1.51	788	2100	4	10	0.50	1.00	22.80	80	1300	950	6.20	85	120	1.62	2.67
	450	1.20	750	2100	4	10	0.33	0.70	23.40	90	1050	1000	6.60	90	125	2.00	2.80
	460	0.84	1075	2350	12	28	0.36	1.05	23.40	80	750	900	6.40	90	130	3.13	2.19
	470	1.00	1113	2100	16	25	0.33	0.60	24.00	100	1100	700	6.40	93	130	1.91	1.89
	480	ND	32	900	ND	10	5.00	1.95	20.40	110	650	500	4.30	15	75	1.38	28.12
	490	1.08	988	2275	16	23	0.28	0.70	24.40	100	1200	1050	7.20	75	130	1.90	2.30
	500	1.53	775	2125	12	25	0.21	0.50	24.40	90	1150	800	6.70	70	130	1.94	2.74
	510	1.23	750	1900	16	25	0.17	0.60	24.40	80	700	1000	6.30	75	140	2.71	2.53
	520	0.91	725	1900	28	35	0.14	0.50	25.60	80	550	900	6.40	65	140	3.45	2.62
	530	0.82	988	1900	44	53	0.21	0.50	25.60	80	600	750	6.20	75	140	3.17	1.92
	540	0.93	375	700	4	5	0.26	4.10	21.80	60	400	800	4.00	48	70	1.75	1.87
	550	1.69	675	1350	70	75	0.11	0.55	25.60	70	700	700	6.00	80	135	1.93	2.00
	560	1.48	725	1325	116	105	0.10	0.55	25.00	60	500	800	5.80	85	140	2.65	1.83
	570	2.30	425	800	106	113	0.14	0.30	26.80	60	650	900	5.70	75	130	1.33	1.88
	580	0.67	3600	4200	320	330	0.30	0.70	22.80	60	600	500	5.70	198	220	7.00	1.17
	590	1.33	1650	2300	196	225	0.29	0.80	25.00	60	750	1000	5.70	115	155	3.07	1.39
	600	1.80	938	1750	96	120	0.38	0.75	24.00	60	900	800	6.00	80	140	1.94	1.87
	610	1.80	1363	2475	142	165	0.41	1.05	22.80	50	1050	850	6.00	78	140	2.36	1.82
	620	1.53	750	1525	64	80	0.30	1.50	22.80	60	750	1000	4.80	55	100	2.03	2.03
	630	0.75	2400	3750	142	160	0.36	0.80	21.80	60	800	800	6.10	95	150	4.69	1.56
195.1	640	0.40	2400	4800	78	83	0.21	0.55	22.80	60	800	700	5.50	88	140	6.50	2.00
	650	0.66	2050	4800	56	65	0.19	0.50	22.80	40	800	750	5.00	75	120	6.00	2.34
	660	0.24	3000	5600	78	80	0.13	0.50	22.80	50	650	800	4.80	93	140	8.61	1.87
	670	ND	4300	6200	767	740	0.11	0.55	20.40	50	700	900	4.80	123	140	8.86	1.44
	684	0.69	2800	6200	178	310	0.11	0.75	21.20	60	1000	1000	7.60	55	120	6.20	2.21
	688	ND	3200	8100	176	210	0.09	0.50	23.40	60	1000	700	5.20	53	125	8.10	2.53
	692	ND	13,000	20,000	336	490	0.11	0.60	23.40	60	1100	700	5.70	130	200	18.18	1.54
	698	ND	4000	8300	64	80	0.14	0.50	26.10	60	1000	800	5.20	73	130	8.30	2.08
	700	0.53	1575	5200	12	20	0.13	0.50	25.60	60	1000	800	5.00	55	110	5.20	3.30
213.4	710	0.89	1013	3550	12	18	0.11	0.40	25.60	60	900	800	4.80	50	110	3.94	3.50
	720	0.42	850	3025	6	10	0.11	0.50	26.10	60	500	750	5.00	58	120	6.05	3.56
	730	1.24	675	2850	4	10	0.10	0.40	26.10	60	700	800	5.00	45	120	4.07	4.22
	740	0.69	550	2725	2	5	0.11	0.35	26.10	60	500	950	5.20	55	120	6.06	3.40
	750	0.71	800	2725	2	5	0.07	0.60	24.00	60	450	1100	5.20	50	120	6.05	3.41
	760	-0.38	763	2725	4	5	0.07	0.30	26.10	60	350	650	5.50	70	110	7.74	3.58
	770	ND	500	2850	ND	5	0.07	0.40	26.60	80	500	800	5.20	35	120	5.70	5.70
	780	0.57	1125	3350	84	108	0.06	0.35	26.10	60	450	800	5.60	58	135	7.44	2.98
	790	0.89	663	2825	4	10	0.07	0.50	27.20	60	500	850	5.70	45	125	5.65	4.27
	800	0.15	950	3075	8	15	0.13	0.50	26.60	60	400	800	5.20	50	120	7.69	3.24
	810	0.93	725	2950	2	8	0.09	0.50	26.60	60	500	800	5.70	45	130	5.90	4.07
	820	0.65	600	2950	2	5	0.07	0.55	26.60	60	400	900	5.20	30	120	7.37	4.92
	830	ND	950	3225	ND	5	0.07	0.40	25.60	60	450	1000	5.40	35	125	7.17	3.39
225.5	838	ND	75	875	ND	5	0.91	0.35	20.40	80	150	700	2.90	2.5	30	5.83	11.66
	850	ND	38	1050	ND	5	2.85	0.35	19.10	70	200	550	3.80	5	40	5.25	27.60
	860	ND	725	2825	ND	5	0.11	1.40	24.40	60	400	1650	5.60	10	120	7.06	3.90
	870	ND	925	3000	ND	5	0.07	0.50	25.00	60	450	800	5.80	35	130	6.67	3.24
	880	0.34	1125	3175	4	8	0.09	0.50	26.10	60	450	900	5.80	35	125	7.06	2.82
	890	0.65	900	3050	2	5	0.09	0.50	26.10	60	450	1000	6.10	30	130	6.78	3.39
	900	0.42	1175	3200	2	5	0.07	0.40	26.10	60	450	800	5.80	38	125	7.11	2.72
	910	0.14	1700	3700	24	35	0.11	0.60	25.60	60	450	800	5.70	50	130	8.22	2.18
	920	0.16	1263	2800	4	8	0.09	0.60	25.00	60	400	700	5.50	45	120	7.00	2.22
298.8	930	0.58	1150	3025	4	10	0.12	0.55	25.60	50	450	800	5.60	40	120	6.72	2.63

Table 15 Geochemical results, canonical scores, and Ni/Cr, Ni/NiP ratios for a single drill hole at Queen Victoria Rocks. In the nickel sulphide zone only Ni and Cu are enriched relative to the komatiite host. At least two komatiite units are present with the contact at approximately 213.4 m.

4.2.2 Forrestania

The Forrestania Nickel Province (Fig. 37) is an extension of the Marvel Lock - Southern Cross "arm" of the Southern Cross greenstone belt (see Section 6.1). There are no recent published geological or aeromagnetic maps of this area. However, it is known that the greenstone belt trends north-south in the north and swings to the southeast south of Forrestania. The belt is linear, strongly metamorphosed throughout and has been partly assimilated into the granitic terrain to the east and west.

Samples were obtained from five diamond core holes representing three separate areas, along a strike length of approximately 20 km. The komatiite sequence is continuous over this strike length, but the dimensions of individual units are not known. All samples were drill core assay pulps representing core intervals of one to five feet (0.32 to 1.57 m). Two drill holes were sampled from Cosmic Boy (holes 1 and 2); one hole from North Endeavor, 8 km south of Cosmic Boy (hole 3); and two holes approximately 3 km apart from Digger Rocks (holes 4 and 5).

Arithmetic means and standard deviations for all chemical determinations and results of individual samples from three drill holes are shown in Tables 3 and 16 respectively. In addition, histograms of results for drill holes 2, 4 and 5 have been plotted as Figs. 38-40.

All komatiites sampled are classified as intrusive, are relatively homogeneous and can be regarded as a single population. The Forrestania komatiites have a distinctive chemical signature and differ in some degree from most other mineralized areas with the exception of Queen Victoria Rocks. Ni (mean - 1980 ppm) and Mg (24.0%) are higher than the mean values for all mineralized komatiites and Cu (24 ppm), Al (0.4%), Ca (1.2%) and Cr (1076 ppm) are significantly lower than the mineralized group mean values. The Ni/Cr

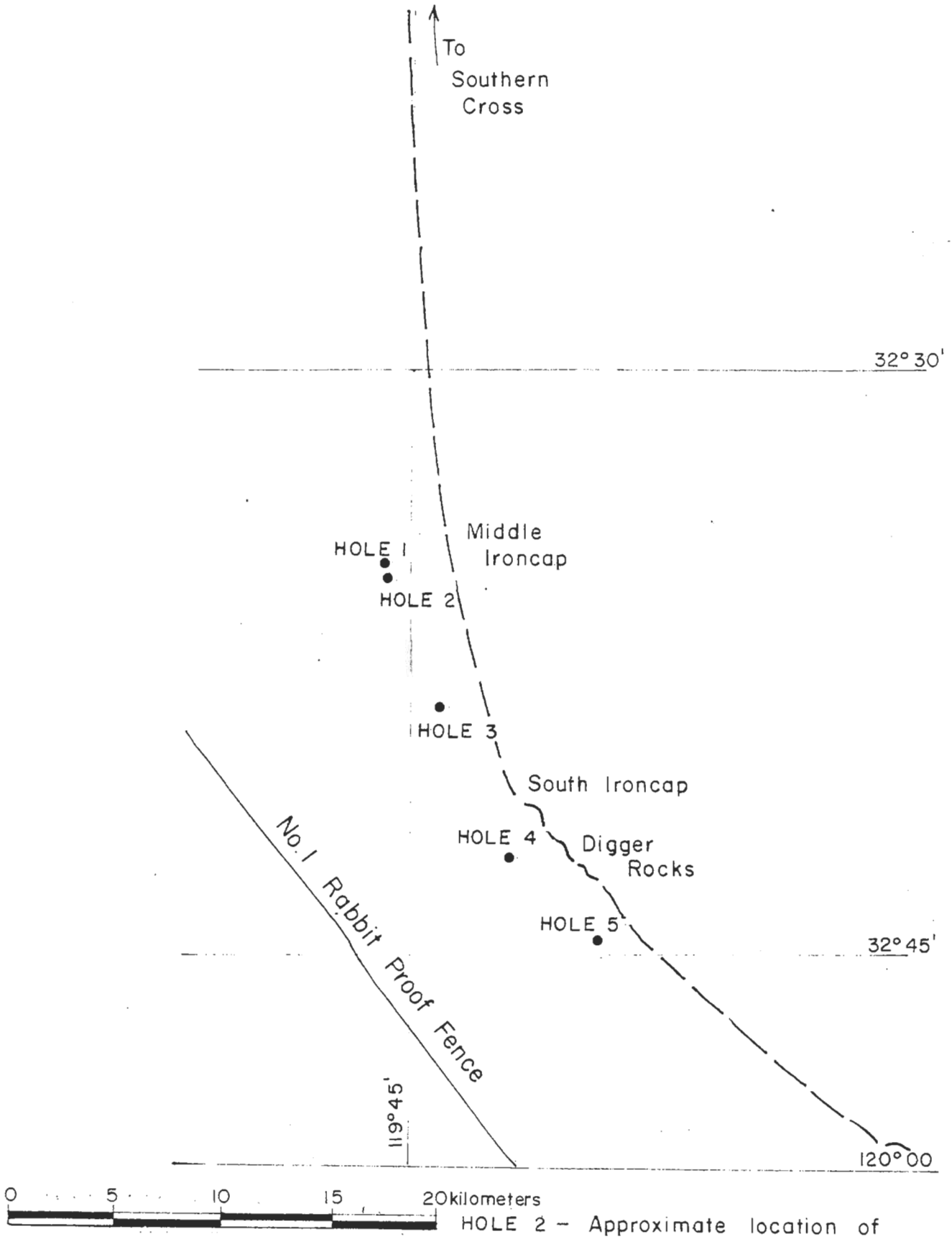

Fig. 37.. Locality plan of drill holes sampled, Forrestania Nickel Province.

Hole No.	Meters	Depth Feet	Canonical Score	NiP	Ni	Cup	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	Ni/Cr	Ni/Ni:
1	212	696-700	1.56	3450	4100	100	117	0.78	2.01	20.00	30	1340	1050	6.50	0.18	103	135	3.06	1.19
		704-707	1.33	1725	2250	124	135	2.60	3.35	16.60	50	1200	1400	8.30	0.52	73	115	1.89	1.30
		1012-1014	ND	2.00%	2.08%	305	375	0.41	1.73	19.20	90	1325	950	11.50	0.08	313	395	15.70	1.04
		1019-1020	ND	750	875	620	680	0.91	0.28	4.40	80	50	400	47.50	0.03	43	140	17.50	1.17
		1022-1026	ND	1.04%	1.20%	525	580	0.23	1.55	23.20	80	825	750	8.60	0.05	138	256	14.50	1.15
		1030-1034	1.27	3850	5300	131	153	0.18	0.75	22.60	50	1350	650	6.90	0.05	83	155	3.92	1.38
		1038-1042	0.51	1738	3125	18	18	0.22	1.01	23.80	40	725	750	5.50	0.05	50	100	4.31	1.80
		1046-1057	1.10	1850	3050	44	53	0.59	0.63	23.80	50	1125	750	6.40	0.10	75	130	2.71	1.65
		1144-1145	ND	1163	1425	124	140	4.90	8.60	7.80	90	325	3250	10.40	0.78	58	105	4.38	1.22
		1148-1153	0.99	1225	2700	24	33	0.84	0.25	24.40	60	1050	1150	7.30	0.18	60	135	2.57	2.20
		1158-1161	ND	1600	2400	320	500	3.60	0.87	20.20	210	700	1850	6.80	0.30	63	125	3.43	1.50
		1187-1191	1.03	513	2000	4	8	2.50	3.86	20.20	60	625	2300	5.70	0.39	25	105	3.20	3.90
		1196-1201	1.48	463	2900	5	8	0.31	0.05	27.20	40	850	650	5.70	0.08	23	125	3.41	6.26
		1206-1211	1.62	525	3050	3	8	0.40	0.02	29.60	40	925	650	6.00	0.08	23	135	3.30	5.81
		1216-1221	1.68	663	2750	2.5	5	0.35	0.35	25.80	40	875	650	5.10	0.08	30	120	3.14	4.15
		1226-1231	1.26	500	2650	3	5	0.48	0.02	26.50	40	925	550	5.50	0.08	25	115	2.86	5.30
		1236-1241	1.10	613	2750	3	5	0.37	0.02	26.50	50	950	600	5.50	0.06	28	120	2.89	4.49
		1246-1251	1.63	650	3000	6	13	0.37	0.02	28.60	40	1000	650	6.00	0.08	28	135	3.00	4.61
		1256-1261	1.26	925	3150	20	23	0.33	0.01	28.60	50	1200	700	6.80	0.05	30	140	2.63	3.41
		1266-1271	1.36	675	2900	18	23	0.35	0.03	29.20	50	1075	950	7.20	0.05	28	135	2.70	4.30
		1276-1281	1.22	850	2850	24	25	0.38	0.02	28.60	50	1075	750	6.10	0.09	33	135	2.65	3.35
		1286-1291	1.45	813	3000	33	38	0.54	0.03	28.00	50	1175	550	6.50	0.12	38	150	2.55	3.69
		1296-1301	1.56	563	2650	40	43	0.50	0.08	27.20	50	1150	800	8.80	0.14	30	140	2.30	4.71
		1306-1311	1.09	1075	2450	45	50	0.88	0.13	25.80	50	1125	500	6.60	0.17	48	120	2.18	2.28
		1312-1314	ND	7650	1.10%	225	335	0.60	5.65	16.40	50	575	2200	10.40	0.12	100	270	19.10	1.44
	402	1316-1319	ND	1.80%	1.88%	950	1040	0.26	0.18	18.00	30	525	500	13.60	0.05	315	490	35.80	1.04
3	120	394-395	ND	7200	7500	230	253	0.59	2.97	19.60	50	800	1050	8.00	0.10	173	200	9.38	1.04
		400-405	ND	4900	5700	205	220	0.45	0.40	23.40	50	775	900	8.00	0.10	168	215	7.35	1.16
		410-415	ND	2250	3150	25	28	0.38	3.93	19.60	80	975	1050	9.90	0.08	108	160	3.23	1.40
		420-425	ND	6700	7600	85	103	0.27	8.00	17.60	60	425	800	6.80	0.05	148	205	17.90	1.13
		430-433	ND	4500	5300	60	73	0.91	10.50	14.80	70	800	1150	7.60	0.20	125	195	6.62	1.18
		436-440	ND	3000	3375	21	28	0.37	1.20	21.80	40	500	600	7.80	0.08	115	145	6.75	1.13
		445-450	ND	3100	3450	129	148	0.40	1.05	21.30	90	525	850	9.10	0.08	135	170	6.57	1.11
		455-460	ND	3550	4000	179	208	0.41	0.85	21.80	50	550	600	10.20	0.10	160	195	7.27	1.13
		523-550	ND	2250	2850	80	98	0.66	9.60	15.00	40	850	1000	5.70	0.12	78	120	3.35	1.27
		555-560	ND	3350	3800	93	113	0.41	1.30	22.20	50	1250	500	7.00	0.09	123	150	3.04	1.13
		564-566	ND	1000	1675	24	25	2.20	1.70	17.60	50	775	400	4.60	0.14	38	80	2.16	1.68
	174	570-572	ND	2250	2575	41	45	0.45	2.56	20.20	30	725	950	5.10	0.08	83	105	3.55	1.14
5	201	660-665	ND	625	2750	2.5	5	0.08	2.65	22.40	60	875	750	5.10	0.03	38	115	3.14	4.40
		670-675	ND	688	2950	3	5	0.07	0.40	24.00	60	975	900	5.60	0.03	40	125	3.03	4.29
		680-685	ND	750	2925	3	5	0.06	0.30	23.40	60	1025	850	5.20	0.03	43	120	2.85	3.90
		690-695	ND	1188	3125	2.5	5	0.06	7.55	16.00	60	825	1450	5.40	0.03	53	125	3.79	2.63
		700-705	ND	838	3000	4	5	0.06	0.55	22.80	60	1075	700	5.80	0.03	43	125	2.79	3.58
		710-715	ND	763	2975	24	25	0.06	0.71	24.00	70	950	1000	5.80	0.03	43	135	3.13	3.90
		720-725	ND	538	2500	10	5	0.12	1.55	22.40	50	775	750	5.50	0.03	28	105	3.22	4.64
		730-735	ND	675	2875	9	13	0.14	0.70	22.80	50	875	850	5.90	0.03	40	135	3.29	4.25
		740-745	ND	663	2700	2.5	5	0.07	2.97	20.60	50	725	850	5.80	0.03	30	105	3.72	4.07
		750-755	ND	850	2975	3	5	0.06	0.70	22.40	50	850	800	5.80	0.03	45	130	3.50	3.50
		760-765	ND	813	2750	3	5	0.10	3.16	20.20	60	700	700	5.60	0.03	35	110	3.93	3.38
		770-775	ND	813	2775	2.5	5	0.15	1.95	22.40	60	825	950	5.50	0.03	40	125	3.36	3.41
		780-785	ND	838	2650	4	8	0.08	0.35	22.40	70	775	800	8.60	0.03	45	115	3.42	3.16
		790-795	ND	900	2850	3	5	0.10	0.93	22.80	70	1025	850	6.20	0.03	40	115	2.78	3.17
	245	800-805	ND	1025	2800	15	8	0.08	0.63	23.40	70	975	750	5.60	0.03	50	130	2.87	2.73

Table 16. Geochemical analyses, canonical scores (B), Ni/Cr and Ni/NiP ratios, for intrusive komatiites in three core holes from the Forrestania Nickel Province. Note the relative homogeneity of the komatiites (excluding obvious nickel sulphide rich samples), with high to very high Ni and Mg and very low Cr and Mn. NiP, and thus Ni/NiP ratios, are variable. Note the different chemical signature of the komatiite between 308 and 322 m., and 362 and 402 m. The upper unit, which is separated from the lower unit by mafic rocks contains much higher NiP (and thus S) and Cu, and is lower in Mg. Both units host nickel sulphides.

ratio at 2.8 and the Ni/NiP ratio at 2.2 are both relatively high.

At Cosmic Boy, several thin intrusive komatiites are separated by sequences of metabasalt and metasediments (Figs. 38 and 39). The basal unit is a banded iron formation. Hole 1 has two main komatiite intercepts with significant nickel sulphides at A and B in Fig. 39 (see also Table 16). Hole 2 shows a similar pattern (Fig. 41). The geochemical results (Table 16) for hole 1 indicate that the two komatiites are chemically distinct (308 to 322 m and 362 to 402 m); the upper unit is considerably richer in Cu (by a factor of 10) and has higher values of NiP than the lower unit. The lower unit shows minor evidence of differentiation with a decrease in the Ni/NiP ratio and an increase in the Cu and TiO_2 values towards the base of the unit. The increase in copper content towards nickel sulphide mineralization may be significant (also occurs at Queen Victoria Rocks).

Two komatiites were intersected and sampled in hole 3 approximately eight kilometers south of Cosmic Boy at North Endeavor. Geochemical results (Table 16) indicate that these ultramafics are similar to Cosmic Boy, with the exception of a lower Mg content. The significance of the lower Mg is not known but it may be related to degree of serpentinization. At Digger Rocks, two holes were sampled, one of which (hole 4) intersected mineralization (Figs. 40 and 42). Two komatiite units with distinct and different chemical signatures are present in hole 4 (45.7 to 251.5 m and 321.6 to 361.3 m); the upper unit contains sulphide mineralization and the lower unit is Barren. The lower barren unit is considerably higher in Cr (factor of three) and lower in NiP. The upper komatiite contains low grade disseminated nickel sulphides towards the top of the unit and more heavily disseminated sulphides at its base. Hole 4 passes downdip of the main mineralization (Fig. 40). Al, Cr and TiO_2 all show a gradual increase in value towards the base of upper unit, whereas Ni decreases (Fig. 42). Mg is a maximum in the center of the unit and decreases towards both contacts. The increase in Cr and TiO_2 towards the base is considered to be a primary differentiation feature

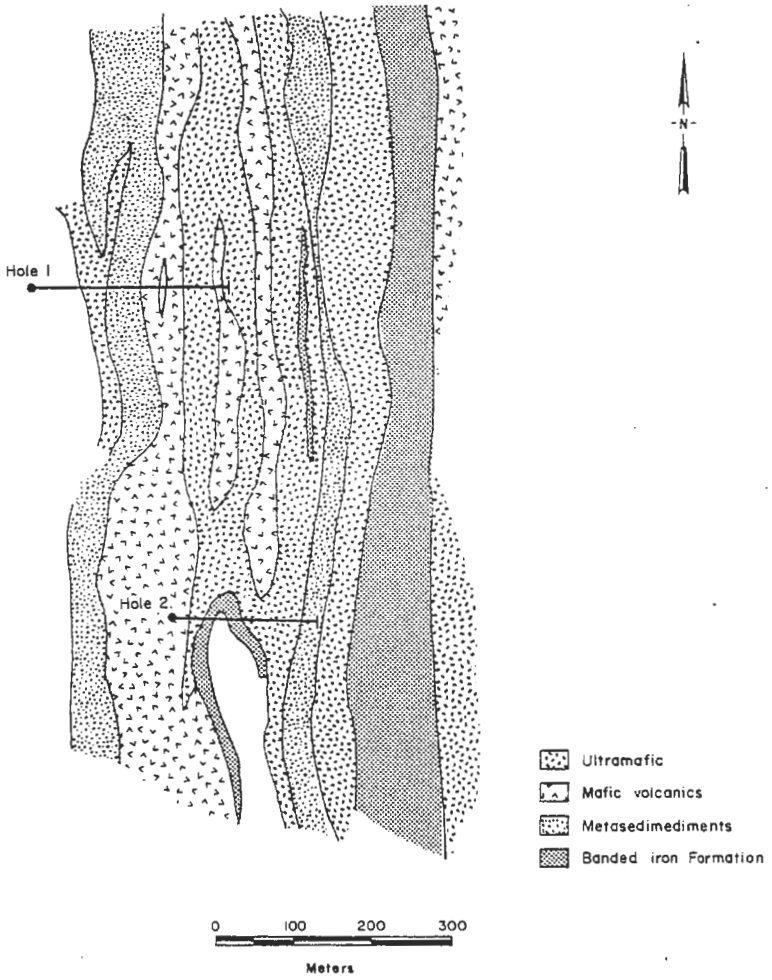

Fig. 38 . Interpretive geology, Cosmic Boy area, Forrestania Nickel Province.

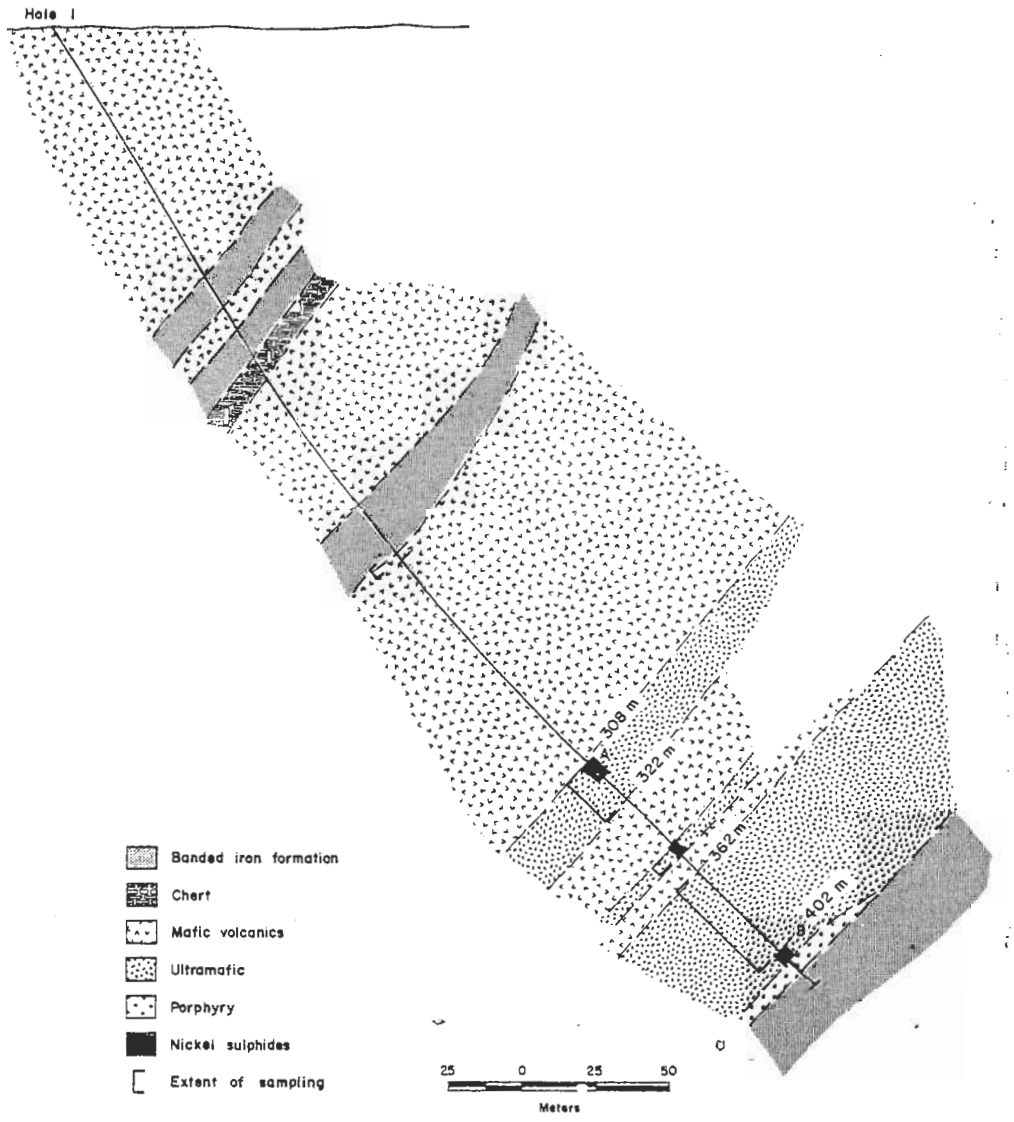

Fig. 39. Geological cross section, hole 1, Forrestania Nickel Province. The ultramafic at A has a different chemical signature to the ultramafic at B

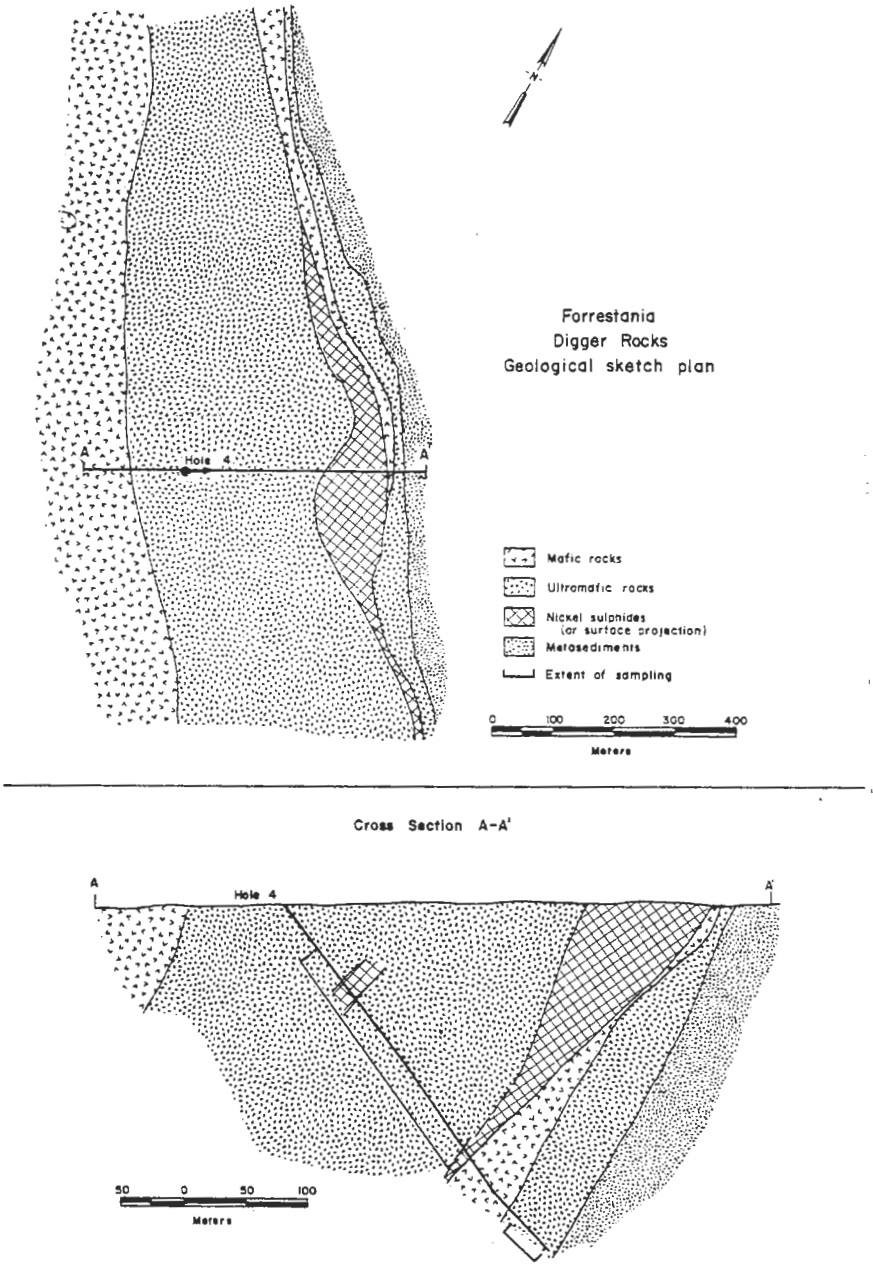

Fig. 40 . Interpretive geological plan and cross section, Digger Rocks, Forrestania Nickel Province. See also Fig. 70.

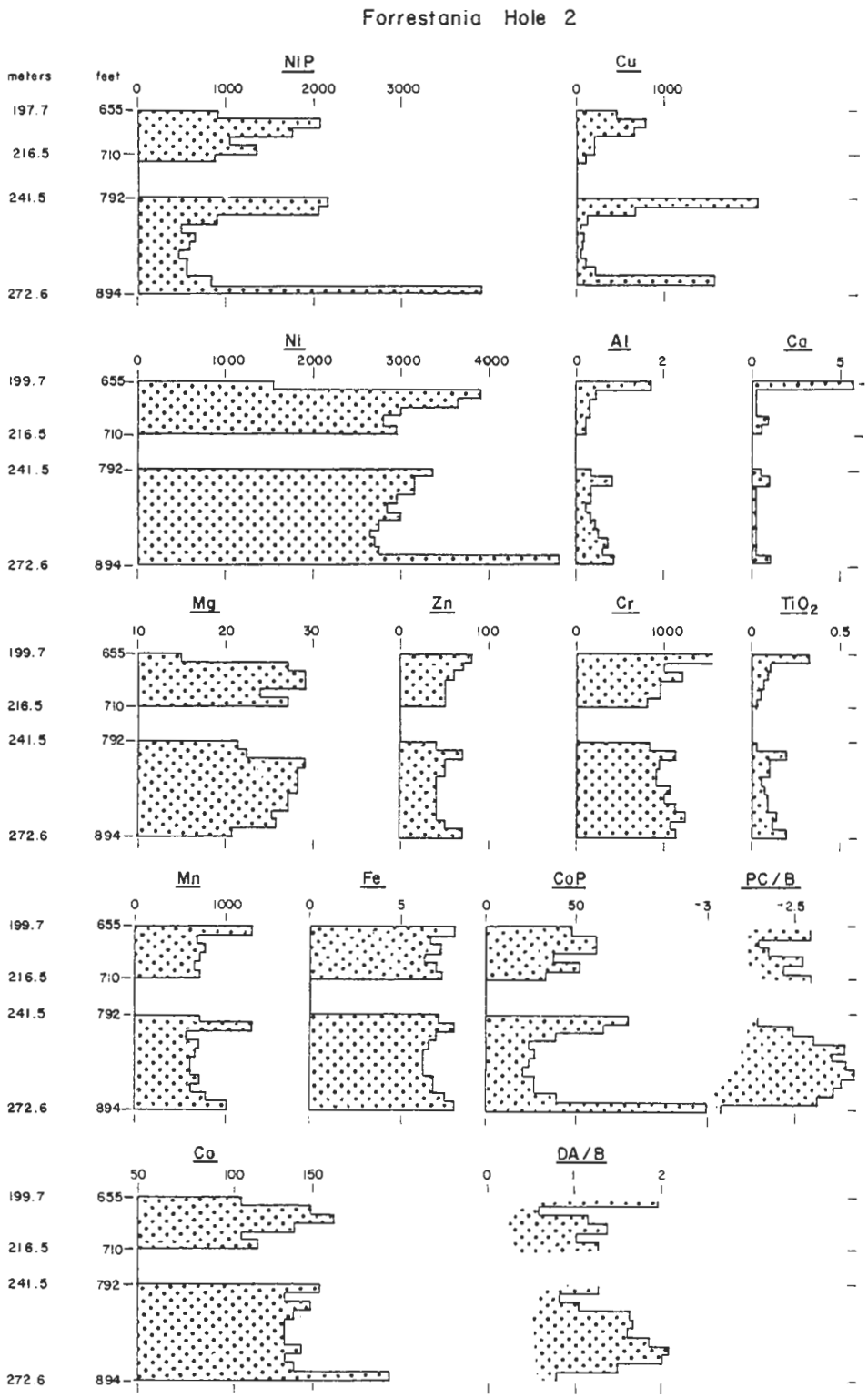

Fig. 41. Histograms of geochemical results, hole 2, Forrestania. Vertical dimension not to scale.

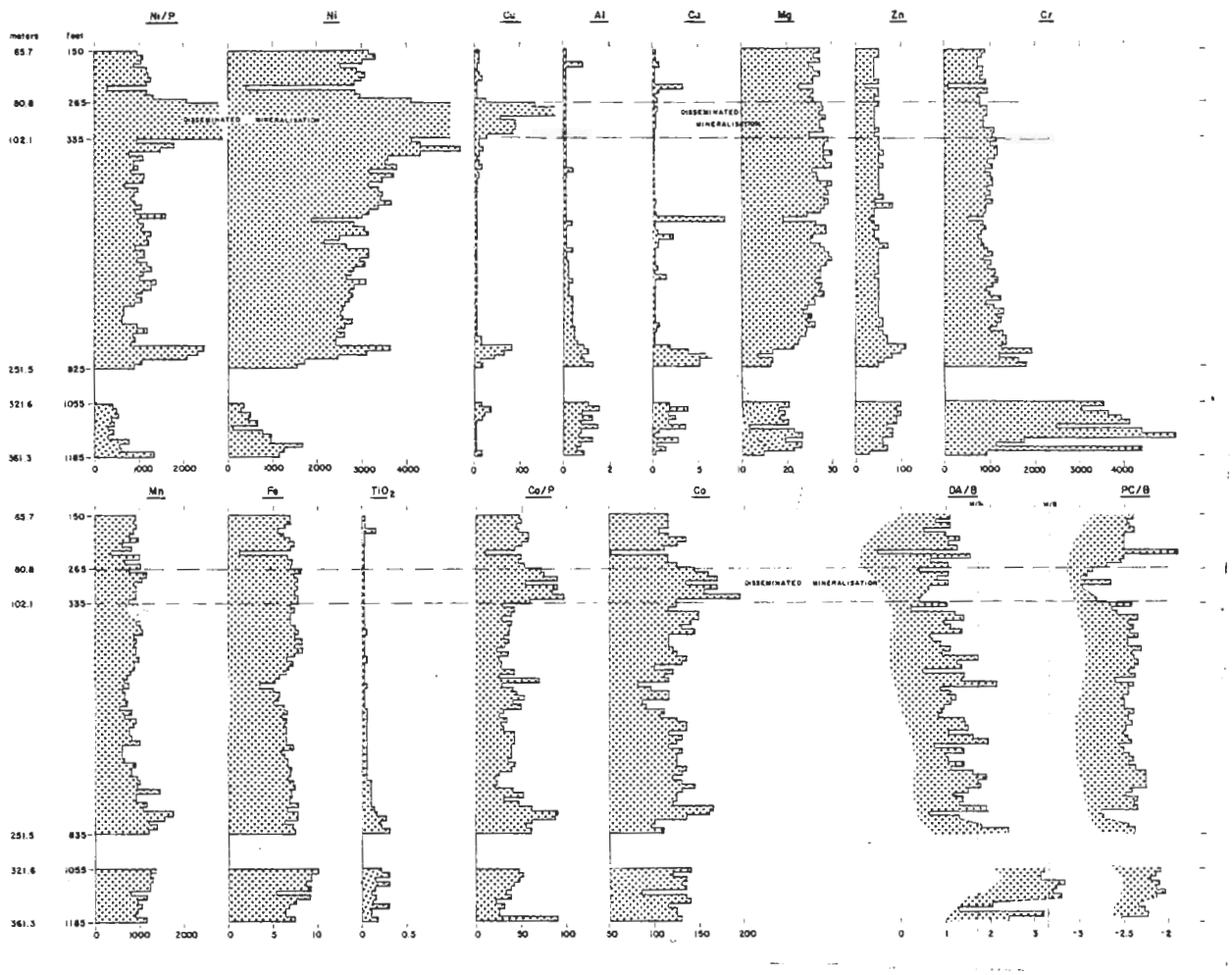

Fig. 42 . Histograms of geochemical results, discriminant analysis A and principal component B scores, hole 4 Forrestania. Note the different chemical signature of the ultramafics above and below 251.5 and 321.6 m. respectively . Disseminated mineralization is present between 80 and 102 m., but the main nickel sulphide mineralized zone is below 251.5 m. The decrease in Ni and Mg towards the base of the intrusive komatiite at 251.5 m. is unusual and may indicate that the nickel sulphide zone is not directly related to the komatiite sampled.

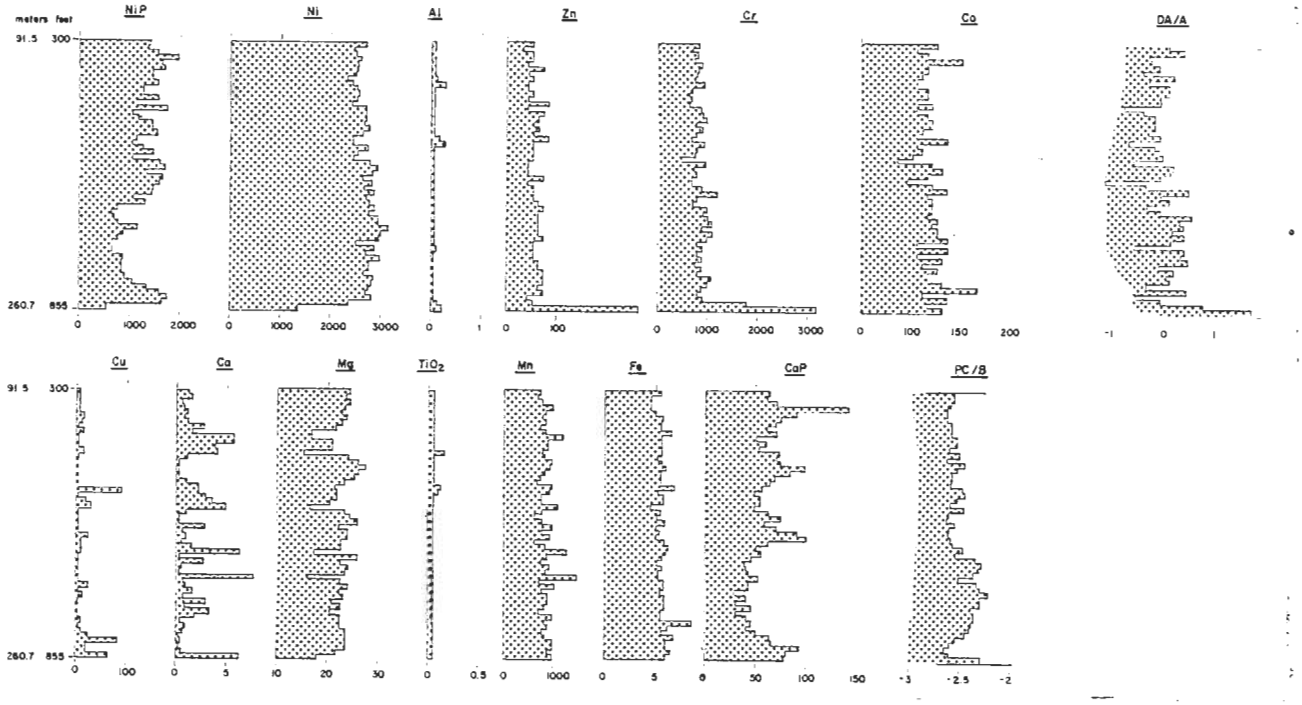

Fig. 43. Histograms of geochemical results, discriminant analysis A and principal component B scores, hole 5 Forrestania. The hole apparently intersected a single komatiite. Note the negative correlation between Mg and Ca, and CoP and Ca, and the homogeneous nature of the intrusive. Hole 5 is approximately 3 km along strike from hole 4, but failed to encounter mineralization.

and confirms that the komatiite sequence is not overturned. The ultramafic between 45.7 and 102.1 m may represent a third komatiite unit, with the disseminated mineralization at the base of the unit. The decrease in Ni content of the komatiite between 102.1 and 251.5 m may indicate depletion of nickel in the ultramafic immediately above higher grade sulphide mineralization (Figs. 40 and 42). Hole 5, which intersects the same komatiite sequence approximately three kilometers southwest of hole 4, did not encounter nickel sulphides. It has a similar but more subdued geochemical signature to hole 4. Geochemical results are plotted as histograms in Fig. 43 and some typical analyses are given in Table 16. The histograms for Ca and Mg (also CoP) show a strong negative correlation which may indicate removal of Mg during talc-carbonate alteration.

Discriminate analysis proved very successful in differentiating Forrestania from the Barren group of komatiites (Table 4) and from most other mineralized komatiites (Fig. 5). Between 93% and 95% of all Forrestania samples were classified correctly in discriminate analyses A and B. Most of the samples which were incorrectly classified were from the basal komatiite in hole 4. As has already been pointed out above, this komatiite has a distinct chemical signature and is apparently not related to mineralization. Discriminate analyses D (Fig. 5) shows that Forrestania is closely related to Queen Victoria Rocks. The geochemical sampling has strongly confirmed that the Forrestania komatiites have a distinct chemical signature and that the mineralized komatiite sequence can be traced over a distance of 30 km. Recent announcements of sulphide intersections further north suggest that the mineralized sequence may have a strike length in excess of 60 km.

4.2.3 Bullfinch

The Bullfinch area represents two parallel komatiite sequences near the

northern end of the Southern Cross greenstone belt (Fig. 28). Both sequences are Barren. Forty spot core samples were taken from four diamond drill holes. Most samples were selected at 12.25 m intervals through komatiites logged as dunite, serpentinite, talcose serpentinite and tremolite-actinolite-chlorite schist. Minor sulphides (0.5% Cu, 0.5% Ni and 0.16% Co) were intersected in a "graphitic schist" unit adjacent to the ultramafic. Holes 1, 2 and 3 represent Bullfinch West and hole 4 represents Bullfinch East (Fig. 44).

Discriminant analyses A and B classified 68% of samples as Barren and 32% as Mineralized. Discriminant analysis D suggests that the Bullfinch komatiites are chemically similar to Mistake Creek. Bullfinch West is a high Mg (mean 24.2%), relatively homogeneous, intrusive komatiite sequence (holes A, B and C, Table 17). It is high in Ni (mean 2110 ppm), has moderate Cr (1581 ppm) and is very low in Cu (9 ppm). Ni$\underline{P}$ values tend to be low, giving rise to high Ni to Ni$\underline{P}$ ratios. On the basis of Ni to Cr ratios alone (mean 1.3), the Bullfinch West sequence could be regarded as having low to moderate mineralization potential. However, the low Ni$\underline{P}$, Cu and Zn values suggest that it is Barren. Compared to other major mineralized intrusive sequences such as Forrestania, Cr values are high. If the komatiites could be regarded as thick units at the base of a volcanic sequence, the geochemical results would suggest that the area had a low mineralization potential. However, as the available evidence suggests the komatiites are in face homogeneous intrusive units, the geochemistry indicates that they are Barren.

4.2.4 Mistake Creek

The Mistake Creek komatiite is an intrusive plug-like body (Fig. 34) of peridotitic and dunitic komatiite and is situated 90 km north of Windarra. No sulphides were encountered within the komatiite and for the statistical

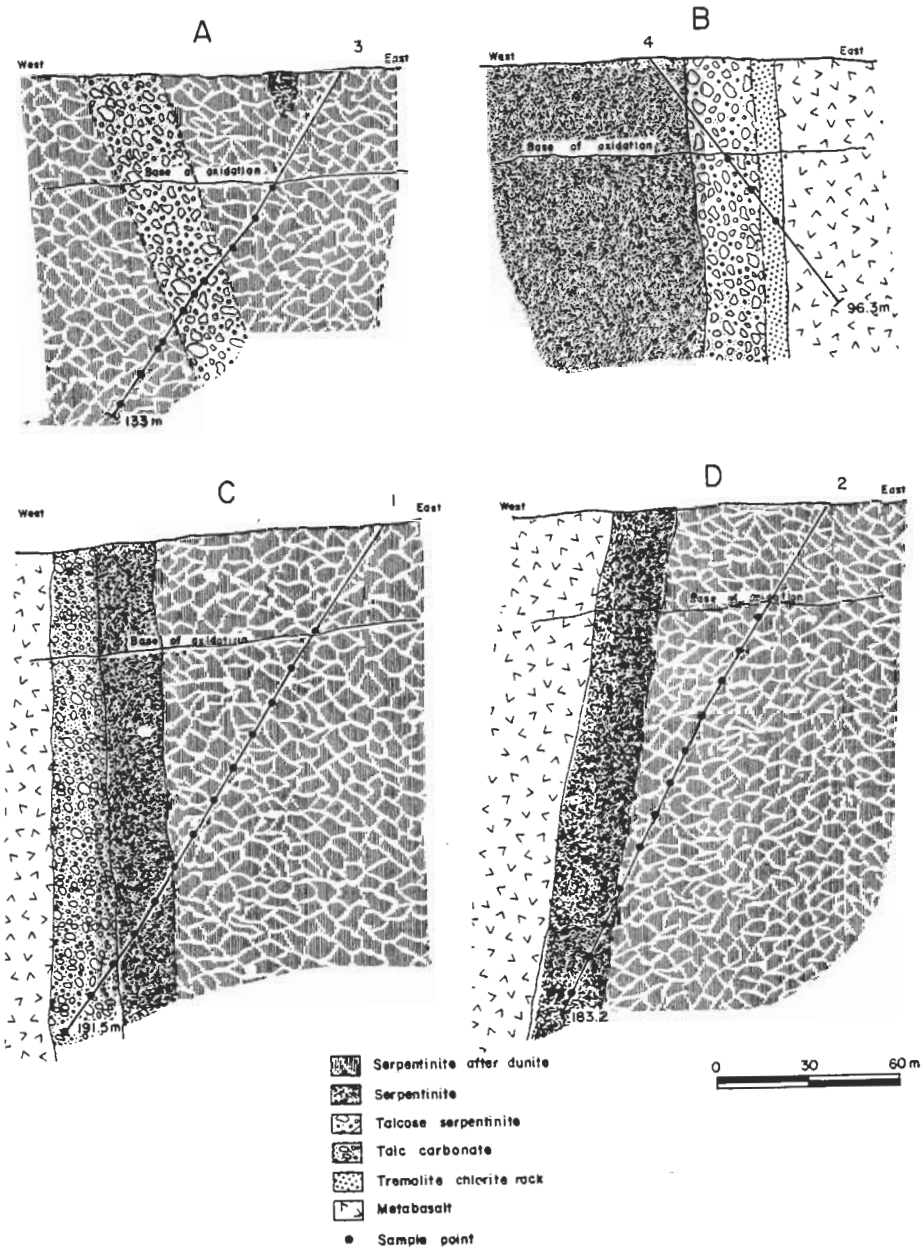

Fig.44 . Geological cross sections of holes 1 to 4, Bullfinch.

Hole No.	Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	Ni/Cr	Ni/NiP
A	41.5	136	2.99	425	2200	2.5	5	0.55	0.03	20.00	20	1450	800	5.60	0.10	53	125	1.52	5.18
		180	2.20	500	2600	2.5	5	0.50	0.04	28.00	40	1250	1050	6.10	0.08	18	130	2.08	5.20
		220	2.54	587	2650	2.5	5	0.21	0.05	29.20	40	1600	950	5.30	0.05	20	120	1.66	4.51
		260	2.80	437	2275	2.5	5	0.27	0.04	28.80	40	1650	750	5.00	0.04	15	115	1.38	5.20
		300	2.97	412	2350	2.5	5	0.37	0.05	29.60	40	1600	850	5.20	0.04	18	140	1.47	5.70
		340	3.15	362	2250	2.5	5	0.17	0.05	27.80	40	1700	800	5.10	0.04	18	125	1.32	6.21
		380	3.11	312	2025	2.5	5	0.31	0.04	27.40	40	1500	850	5.80	0.04	15	135	1.35	6.49
		420	4.07	350	2100	2.5	5	0.20	0.34	27.40	40	2650	900	6.10	0.04	15	135	0.79	6.00
		460	3.37	600	2075	2.5	5	0.40	0.04	22.40	20	1900	850	4.60	0.07	35	110	1.09	3.45
		500	4.14	225	1700	2.5	5	0.52	0.07	20.80	20	2250	450	4.00	0.08	13	90	0.76	7.56
		540	3.30	612	1450	2.5	5	0.22	0.07	20.50	30	1350	1050	5.20	0.03	20	110	1.07	2.37
		580	3.50	775	1900	23	18	0.65	0.50	19.60	30	3200	750	6.00	0.11	38	115	0.59	2.45
	190	624	4.02	400	1300	26	33	0.72	6.25	15.60	50	2750	1950	5.70	0.18	48	110	0.47	3.25
B	42.7	140	2.36	600	2400	9	13	0.60	0.29	22.00	60	1700	1250	8.20	0.14	28	145	1.41	4.00
		180	2.99	375	2025	20	28	0.55	0.55	22.00	60	1800	1250	6.80	0.13	15	125	1.12	5.40
		220	3.56	125	1825	5	8	0.57	0.44	21.20	50	1850	950	5.80	0.13	8	110	0.99	14.60
		265	2.13	412	2400	3	5	0.50	0.33	24.00	60	1250	1150	7.50	0.07	18	140	1.92	5.82
		281	1.88	425	2350	6	8	0.58	0.45	22.60	40	900	1000	6.10	0.08	25	125	2.61	5.53
		300	1.86	387	2400	13	15	0.50	0.12	22.60	50	950	950	6.70	0.08	13	125	2.53	6.20
		339	2.03	812	1650	3	5	0.26	4.75	22.00	30	700	1900	3.50	0.08	23	80	2.35	2.03
		340	1.91	757	2800	3	5	0.22	0.75	25.20	60	1200	1500	9.20	0.08	43	170	2.33	3.70
		380	0.88	687	2725	4	5	0.43	0.40	25.60	50	700	1050	6.40	0.07	33	130	3.89	3.97
	128	420	1.80	500	2825	2.5	5	0.34	0.41	28.00	40	800	1000	6.10	0.05	20	130	3.53	5.65
C	163	140	2.72	587	2550	2.5	5	0.40	0.12	26.40	40	1750	900	5.80	0.05	20	125	1.46	4.34
		180	2.89	487	2650	2.5	5	0.11	0.04	29.60	40	1500	1000	5.70	0.03	20	140	1.77	5.44
		220	5.34	25	875	2.5	5	0.38	0.34	24.00	20	1900	500	3.40	0.07	25	70	0.46	35.00
		260	2.58	600	2550	2.5	5	0.25	0.24	26.80	30	1100	900	6.60	0.05	25	140	2.32	4.25
		300	2.28	425	2375	2.5	5	0.47	0.06	28.00	40	1000	1050	6.20	0.11	23	150	2.38	5.59
		340	2.62	337	2200	2.5	5	0.56	0.04	27.40	30	1000	950	5.70	0.10	18	140	2.20	6.52
		380	2.73	500	2450	3.0	5	0.34	0.04	27.40	30	1450	850	4.80	0.05	18	125	1.69	4.90
		410	2.52	625	3200	3.0	5	0.18	0.05	28.40	40	1700	950	5.70	0.04	15	130	1.88	5.12
		460	2.88	412	2200	2.5	5	0.37	0.03	27.80	30	1300	800	4.60	0.07	18	125	1.69	5.33
		500	1.86	600	2200	3.0	5	0.46	0.12	27.00	30	700	750	5.60	0.08	20	135	3.14	3.67
		540	3.03	450	2450	3.0	5	0.17	0.07	28.40	40	1700	1000	5.60	0.04	18	140	1.44	5.44
	177	580	4.40	112	1250	2.5	5	0.43	0.22	24.60	20	1950	350	3.10	0.05	10	75	0.64	11.16

Table 17. Representative komatiite sample results from three core holes at Bullfinch. This ultramafic sequence is relatively homogeneous, peridotitic to dunitic in composition, and is probably intrusive. The mineralization coefficient of the sequence as a whole is just on the Barren side of the Mineralized-Barren dividing point. Cr values are moderate and Ni relatively high, giving Ni/Cr ratios in many cases of greater than 1. However NiP (S) values are low, and although the Cr values are moderate in terms of all komatiites in the Yilgarn, they are still relatively high for Mineralized intrusive units. Thus the sequence as a whole is regarded as Barren.

analysis it was classified as Barren. Outcrop is extremely poor and the geology was compiled from geochemical drill hole data and from rotary drill hole cuttings. Rocks adjacent to the komatiite (based on drill cuttings only) are mainly amphibolites, although some pyrite rich sediments were encountered.

Sixteen samples of komatiite from two core drill holes were examined petrographically. These samples were all serpentinites or serpentine-talc-carbonate rocks. Minor chlorite was noted in two rocks. Cumulate olivine textures occur in all samples, with olivine grains 0.5 to 5 cm in diameter, now replaced by serpentine minerals. Estimates of original olivine content ranged from 70% to 90%. Limonite, chromite and magnetite are present as accessory minerals. Seventeen spot core samples (4-5 cm long) from two core holes and 26 chip samples from rotary holes were used in the discriminant analyses. The results from nine core samples shown in Table 12 confirm that the komatiite is of olivine peridotite or dunite composition. In addition, the komatiite is high in Ni and some samples are low in Cr, which gives rise to results with moderate coefficients of mineralization. However, the Cu content is extremely low and the net effect of all geochemical variables is to suggest that this komatiite is in fact Barren.

CHAPTER 5

EVALUATION OF WONGANOO - BANDJAWARN GREENSTONE BELT

The Wonganoo-Bandjawarn greenstone belt is located approximately 330 km north of Kalgoorlie in the extreme northeast of the Wiluna-Norseman belt of Gee (1975). Samples of komatiite were obtained from seven separate komatiite sequences (Fig. 45). On the basis of available data, one area was originally considered to be Mineralized and the remaining areas Barren.

The chemical and discriminant analysis results for each area within this greenstone belt are evaluated below as examples of how the criteria developed in this study can be applied in practise.

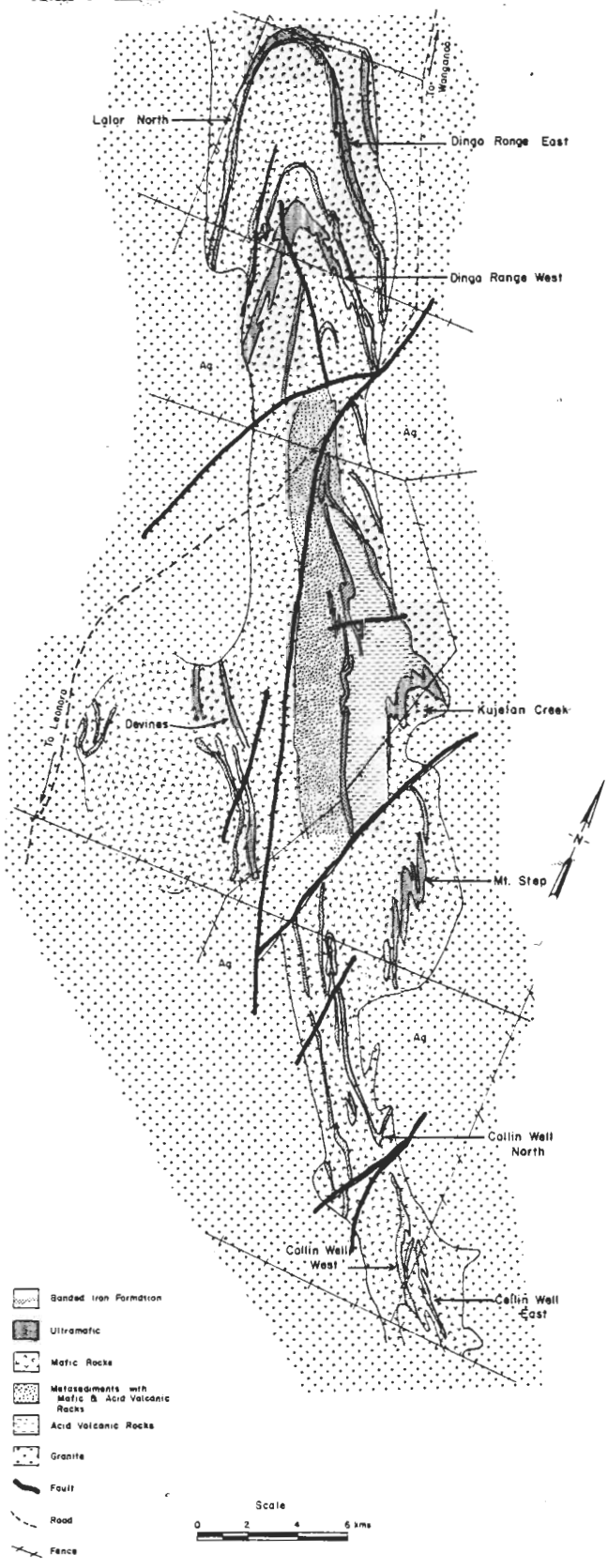

Fig. 45. Interpretive geology of Wonganoo-Bandjawan Greenstone Belt including the following structural units: Dingo Range-Lalor North; Mt. Harold-Kujevan Creek; Mt. Step-Collin Well; and Sterling Peaks.

5.1 GEOLOGICAL SETTING

The greenstone belt is surrounded by granitic rocks to the east, west and south and is gradually absorbed into granitic terrain to the north where it can be traced intermittently for 130 km north of Wonganoo. To the south of the Wonganoo-Bandjawarn greenstone belt, an intermittent magnetic feature which may represent a granitized greenstone belt, can be extrapolated south to connect with the Windarra Nickel Province.

The greenstone belt is essentially anticlinal, which is in contrast to the normally accepted view that most greenstone belts represent synclinal keels (Fig. 45). Faulting has divided the belt into four structural units: the Dingo Range-Lalor North Unit, Mt. Harold-Kujelan Creek Unit, the Mt. Step-Collin Well Unit and the Sterling Peaks Unit. Depending on interpretation of these faults, it can be assumed that the stratigraphy represents a continuous series, younging to the northwest, or that the stratigraphy from block to block is not directly related.

In the Dingo Range-Lalor North Unit the stratigraphy from oldest to youngest is as follows (Fig. 46):

1. A series of deformed and closely folded amphibolites after metabasalts, with discontinuous ultramafic horizons, and minor metasediments. Pillow structures have been noted near the top of the sequence.
2. Overlying these metabasalts is a komatiite sequence (Dingo Range West) which passes upwards into amphibolites and metasediments and finally into a banded iron formation. This banded iron is in part finely bedded and contains considerable limonite after sulphides. No drill holes have penetrated this unit.
3. A second sequence of uniform, fine-grained amphibolites after basalt overlies the banded iron formation. It is intruded by coarse-grained gabbroic rocks on the western flank of the anticline. The sequence is

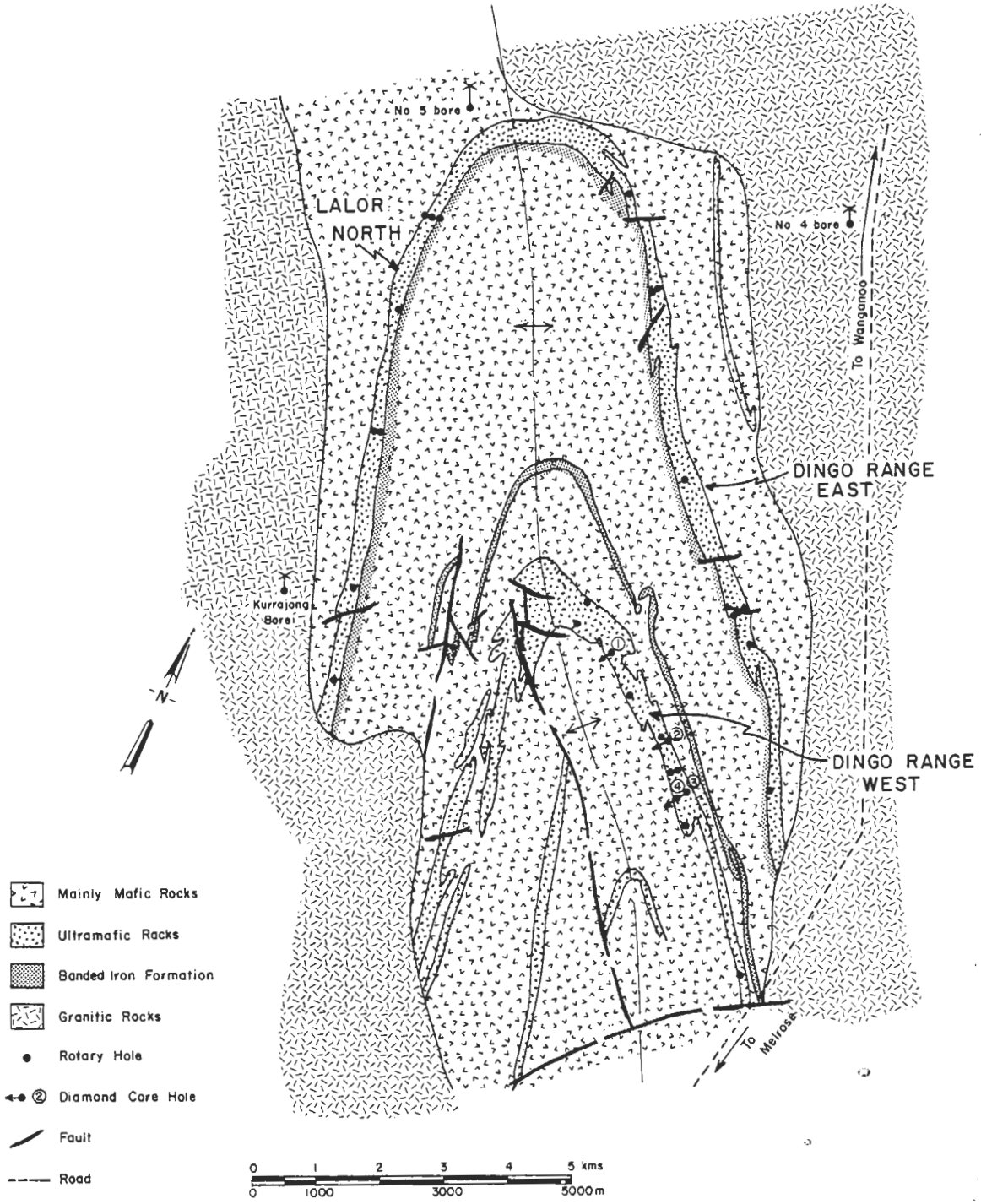

Fig. 46 . Interpretive geology of Dingo Range-Lalor North area showing location of komatiite ultramafic sequences and drill holes sampled.

terminated by a second banded iron formation. This banded iron is similar in appearance to the lower banded iron formation, is well bedded and extensively crenulated and folded.

4. Immediately overlying and apparently in contact with the banded iron formation, is a further sequence of komatiites, passing upwards into a metabasalt sequence with minor intercalated sedimentary and ultramafic units. This upper komatiite sequence (Dingo Range East and Lalor North) rarely outcrops and very little is known of its internal structure. It contains a semi-continuous, centrally located gabbroic, sill-like body in the Dingo Range area (Fig. 44).

The east limb of the Dingo Range West komatiite sequence dips east at 70 to 85 degrees but the Dingo Range East banded iron formation and komatiite sequence are overturned and dip steeply (80 to 85 degrees) west. The Lalor North area and the west limb of Dingo Range West area are completely obscured by Quarternary deposits.

The Mt. Harold-Kujelan Creek Unit forms the central section of the Wonganoo-Bandjawarn greenstone belt and contains the Kujelan Creek area. Structurally, it consists of an extremely tight anticlinal fold which is outlined by a thick, well developed banded iron formation (Fig. 45). The lowermost stratigraphic unit is a complexly folded mafic-ultramafic sequence known as Kujelan Creek. This sequence does not outcrop and has been defined from extensive geochemical drilling, deep rotary drill holes and aeromagnetic data. Overlying the Kujelan Creek sequence are a series of acid volcanics, crystal tuffs, fine-grained pyroclastics and rare lavas. These rocks are now kaolin, sericite, quartz schists. The acid volcanic sequence is terminated by a thick, complexly folded and contorted, banded iron formation which is sulphide rich in part.

The Mt. Step-Collin Well Unit represents a relatively narrow remnant of the greenstone belt at the southern end of the Wonganoo-Bandjawarn belt and differs from the previous units in having a well developed northwest linearity in both banded iron formation and komatiites. The structure has been tentatively interpreted as synclinal. The Mt. Step komatiite sequence is complexly folded and probably disrupted by strike faulting. It is underlain and overlain by amphibolites of unknown origin and is associated with a large, presumably intrusive gabbroic mass to the west. Metasediment bands are common within both the komatiite sequence and amphibolites. Outcrop is extremely poor and all geological data is derived from drill holes. At Collin Well the mafic rocks include metagabbros and metabasalts and high Mg basalts outcrop in the eastern part of the area. The banded iron formations shown in the western part of the Mt. Step-Collin Well unit (Fig. 45) have variable magnetic intensity and some appear to be banded cherts.

The Sterling Peaks Structural Unit contains the Devines' (Fig. 45) nickel prospect and the geology is considered to correlate with the Dingo Range area. The geology of this area is not well known but appears to be dominantly amphibolites with some interlayered komatiites and banded iron formation. The Devines komatiite sequence is tentatively correlated with the Dingo Range West komatiites.

5.2 EVALUATION OF INDIVIDUAL AREAS WITHIN THE GREENSTONE BELT

Dingo Range West and Devines will be described separately but Lalor North-Dingo Range East and Mt. Step-Collin Well areas will be grouped because of probable geological continuity between these respective areas.

5.2.1 Dingo Range West

The Dingo Range West (Fig. 46) komatiite sequence is heterogeneous, has a strike length of 12 kms and ranges up to a maximum width of 400 m. It is a volcanic suite but thick sequences of thin units are absent. It was assigned to the Barren komatiite category for the statistical analysis.

5.2.1.1 Geology

The komatiite sequence forms a steep sided anticline which plunges to the north at approximately 50 degrees (Fig. 46). Little is known of small scale structure but the distribution of ultramafic rocks and intensive folding, crenulation and apparent disruption in the overlying banded iron formation indicates that tectonic disturbance is intense. Outcrop is restricted to the east limb of the Dingo Range West komatiite where it is sporadic and limited to the main banded iron formation and silicified (caused by weathering) sedimentary horizons such as pyritic black shales. Geological information was derived mainly from four diamond core holes, numerous geochemical drill holes and deep rotary drill holes.

The komatiite footwall rocks were penetrated by two diamond drill holes (1 and 4 - Fig. 46). Hole 1 intersected the following rock sequence: one meter of sulphide rich black shale underlain by 30 m of metagabbro; 10 m of carbonate and sulphide rich sediment and an unknown (the drill penetrated 40 m) width of amphibolites. In thin section,

the gabbro is medium to fine-grained and consists of saussüritized plagioclase, augite and interstitial material composed of quartz and alkali feldspar. The grain size averages 0.5 mm, primary hornblende is absent and felsic and mafic components occur in approximately equal amounts. The carbonate rich sediments consist of banded, magnesium-rich carbonate, fibrous tremolite and subordinate mica. Tremolite occurs in subradiating aggregates and some sections are magnetite rich. Sulphide content is variable but ranged as high as 20% and consists mainly of pyrite with subordinate chalcopyrite. Cu content varies up to 0.12% over a core length of 3.1 m. The amphibolites consist of porphyroblastic actinolite with moderate preferred orientation, in a fine-grained ground-mass (0.01 mm) of plagioclase feldspar and altered mafic material. Biotite is developed locally and some sections of the amphibolite are banded with thin bands of finer-grained, less porphyritic material. The amphibolites are interpreted as being mainly metabasalts. In hole 4, sulphides were intersected in an actinolite schist (pyrite, pyrrhotite, marcasite and chalcopyrite) which formed the komatiite footwall.

No detailed geological data is available for the amphibolites, sediments and banded iron formation which overlie the komatiite sequence.

5.2.1.1 Komatiite Sequence

Unweathered komatiite was intersected in three diamond core holes and two of these holes (holes 3 and 4 - Fig. 48) represent a section through the basal 280 m of the sequence. These sections illustrate the stratiform nature of the sequence, with interlayered sulphide rich graphitic shales and mafic volcanics. Few primary textures are

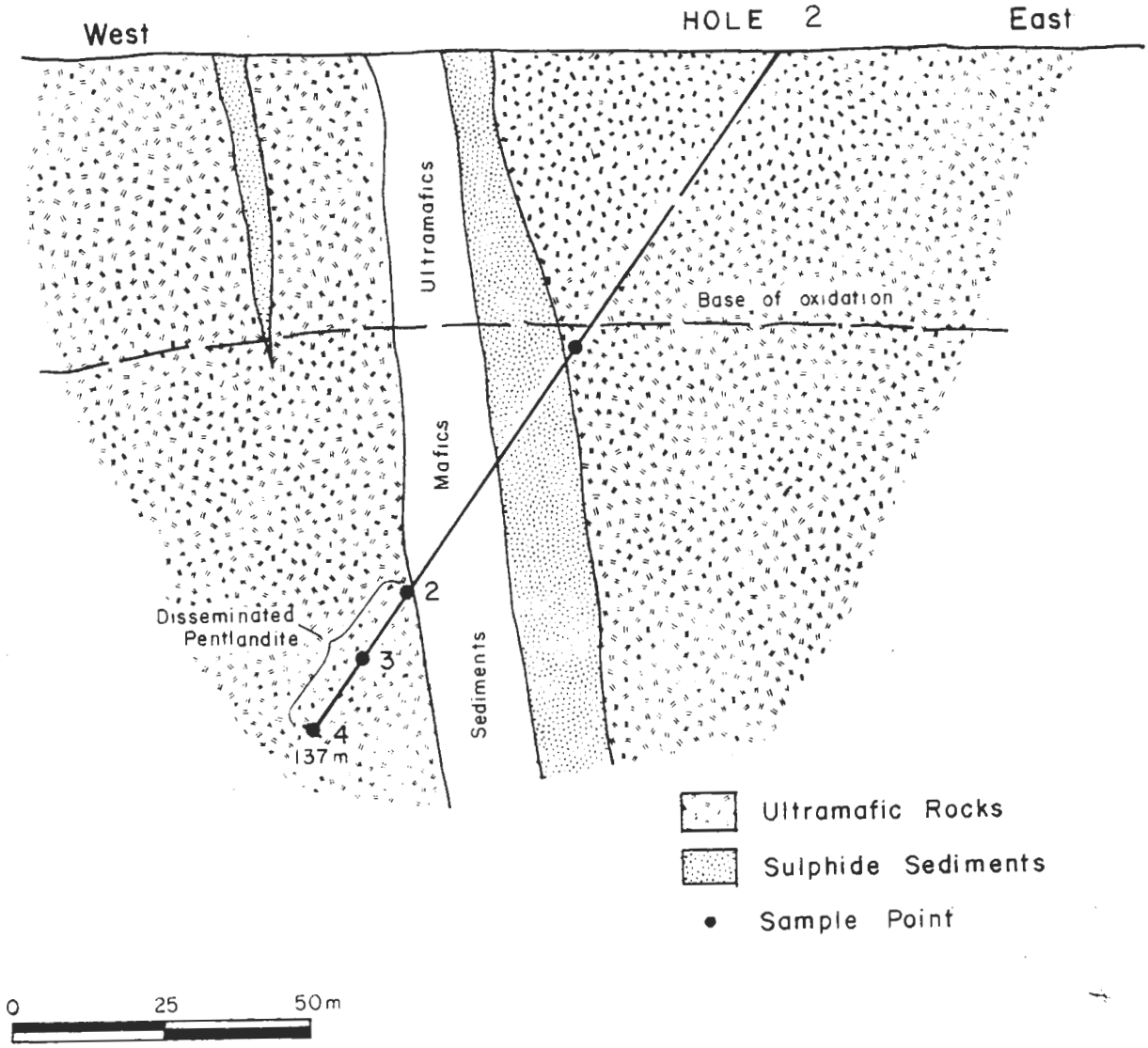

Fig. 47. Geological Cross Section, drill hole 2 Dingo Range West, showing location of core samples.

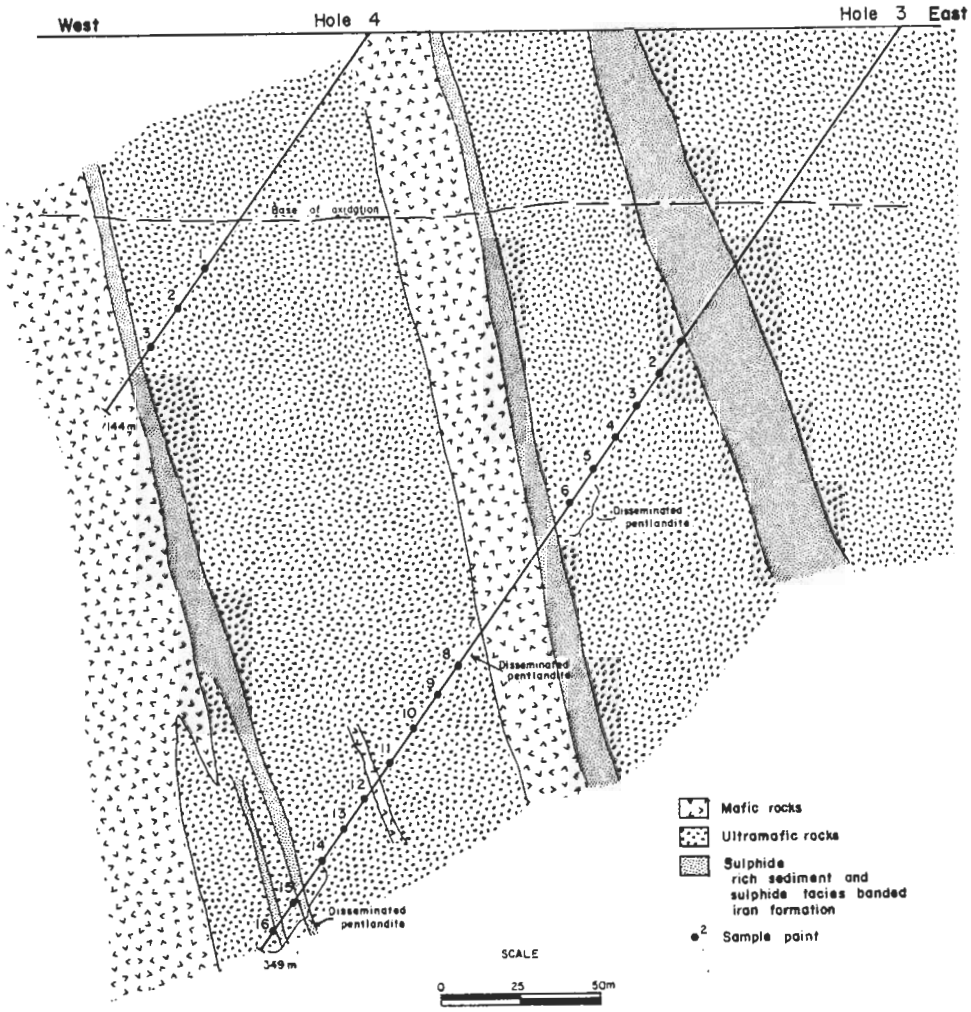

Fig. 48. Geological Cross Section, drill holes 3 and 4, Dingo Range West, showing location of core samples.

retained in the komatiites; spinifex texture was noted in one place only and textures after olivine are rare. Boundaries between individual komatiite units were not identified microscopically or macroscopically.

In hole 2 (Fig. 47) the eastern section of komatiite is low in Mg and consists mainly of talc-carbonate-chlorite schist with minor magnetite. The ultramafics in the intermixed ultramafic sediment zone are chlorite rich and contain minor sulphides - mainly pyrite, but with traces of chalcopyrite, covellite and sphalerite. The interlayered sediments vary from graphitic schists with locally well developed pyrite to schistose quartz sediments. Altered igneous, soda rich porphyries and amphibolites after gabbros also occur. These rocks also contain pyrite and are relatively rich in talc, possibly due to metasomatic transfer from the ultramafic rocks. The ultramafics underlying the mixed sediment - ultramafic zone consists of talc-carbonate-chlorite rocks grading to serpentine-talc-carbonate rocks (to the west). This zone has a width of more than 20 m and represents a single komatiite. Disseminated sulphides occur erratically throughout this zone, varying from a trace to 3% by volume. Sulphides include pyrrhotite, pentlandite, pyrite and chalcopyrite. Pyrrhotite-pentlandite ratio varies from 3:1 to 6:1. Chromite and magnetite are accessories. Pyrite appears to be associated primarily with carbonate.

Holes 3 and 4 can be interpreted to give a stratigraphic sequence as follows (Fig. 48):

1. The first and eastern-most unit is a talc-carbonate-chlorite schist with rare serpentinite and ranges from moderately magnetic to non-magnetic.

2. The second unit is a composite metasediment zone with some included ultramafic. From top to bottom it consists of the following subdivisions:

   2a. 1 m thick zone of graphitic, sulphide-rich shale.

   2b. 2 m of tremolite-chlorite rock. This unit consists of fibrous tremolite with non-schistose distribution and subordinate platey chlorite. It possibly represents a pyroxene rich ultramafic.

   2c. Volcanic, probably extrusive rock consisting of sodic plagioclase, potash feldspar, subordinate quartz and minor actinolite.

   2d. 9 m thick zone of graphitic, sulphide-rich shale.

3. The third unit is ultramafic (width 50 m), consists of talc-chlorite-carbonate rock in the top 6 m, grading to massive serpentinite below. The serpentinite consists of antigorite, with minor talc and chlorite and varying but significant amounts of magnetite. Relict olivine textures are rare and where present are indistinct. Sulphides are present in the basal 10 m of this unit and consist of pyrrhotite, pentlandite and chalcopyrite. Chromite is also present in this zone. The ultramafic is interpreted as a single, differentiated komatiite, (thick unit) predominantly olivine peridotite with a pyroxene rich upper section.

4. Underlying unit 3 and separated by a 3 m thick transition zone in which the ultramafic and the sediments are intimately mixed is a further sequence of sulphide rich, graphitic sediments. The transition zone is a schistose, ultramafic rock, with idioblasts of tremolite in a groundmass of fine-grained talc and chlorite.

The rock contains 25% tremolite, 50% talc, 5% chlorite and 20% sulphides. (Pyrrhotite - 90%, chalcopyrite - 9 % and sphalerite - 1%; pentlandite is absent).

5. This unit consists of metasomatized basic rocks, now actinolite-chlorite schists.

6. Underlying unit 5 is a further komatiite sequence which consists mainly of talc-carbonate schist in the upper part, grading to serpentinite towards the base. The ultramafic is 70 m thick and probably represents two komatiites, separated by a three-meter thick band of amphibolite. The upper contact with overlying basic rocks is gradational. Minor pentlandite (without pyrrhotite) occurs in the upper part, and millerite, chalcopyrite and pyrrhotite occur in the lower section of the basal unit, changing to pyrrhotite, pentlandite, niccolite and chalcopyrite just above the base. Pyrrhotite-pentlandite ratio is 9:1 and total sulphide content is one percent. A thin zone of talc-chlorite-carbonate schist occurs at the base.

7. A 3 m thick band of sulphide rich graphitic shale forms the footwall of this komatiitye.

8. Underlying the sulphide rich sediment is a basal komatiite sequence of unknown width. A 1 m thick, finely laminated sulphide rich, graphitic shale band occurs 10 m below the top of the komatiite. This komatiite is a chlorite free, talc-carbonate schist, with one percent sulphide (equal quantities of pyrrhotite, niccolite and pentlandite). Relict chromites are present.

9. The basal, footwall unit to the komatiite sequence is fine-grained amphibolite, probably after basalt.

Hole 4 which intersected units 6 and 7, some 200 m up-dip, passed directly from unit 7 into footwall amphibolites.

5.2.1.3 Geochemistry

Samples were collected from holes 2, 3 and 4 (representing a 300 m width of ultramafic) and from five deep rotary holes. Samples included core pieces and composite assay pulps from the core drill holes and drill chips from rotary holes. Results from core chips only are shown in Table 18.

The discriminant analysis results (Table 4) suggest that the Dingo Range West group may have originally been incorrectly assigned as Barren. Discriminant analysis A classified 56% of samples and analysis B 62% of samples as Barren. Most samples with mineralized scores are concentrated in the basal komatiite units. In hole 3 (Fig. 48 - Table 18), samples are widely spaced (12.2 m intervals) but together with other analyses from core pulps (not shown here), are sufficient to suggest that samples 1 to 6, 7 to 11 and 12 to 14 each represent separate komatiite units. These komatiites are predominantly olivine peridotite or dunite cumulative rocks, (thick units) with thin low magnesium upper sections (representing silicate liquid portion). Ni and NiP are relatively constant throughout hole 3, but chromium decreases towards the basal contact. Sulphur and NiP are not highly correlated: sample 15 has moderate sulphur content (0.23%) but low NiP (560 ppm); sample 14 has a high NiP content (2150 ppm), low Ni/NiP ratio (1.06) but contained only 0.085% sulphur. In hole 2, sample 2 contained 1.29% sulphur but only 260 ppm NiP. The komatiites in hole 2, although comparable in Mg content to hole 3, are lower in nickel

Hole No.	Sample No.	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	S	Ni/Cr	Ni/NiP
DR 2	1	2.68	275	1675	20	25	2.10	2.90	15.50	70	2250	1000	6.50	0.17	40	100	0.010	0.74	6.09
	2	3.47	260	1650	28	50	1.60	9.05	13.60	40	800	1500	5.85	0.20	55	110	1.290	2.06	6.34
	3	2.41	475	1675	52	53	1.65	0.14	20.70	30	1200	800	7.70	0.17	37	80	0.240	1.39	3.52
	4	2.26	540	1450	4	5	1.55	1.25	20.40	30	900	1150	6.80	0.13	57	140	0.050	1.61	2.68
DR 3	1	2.41	690	2175	16	15	1.40	0.54	19.70	30	1650	700	5.90	0.07	47	120	0.035	1.32	3.24
	2	2.42	575	2225	2	2	1.40	0.95	21.40	40	2100	700	5.65	0.13	32	120	0.035	1.06	3.86
	3	2.49	310	2175	2	2	1.55	1.05	22.40	30	1650	750	6.25	0.07	30	120	0.015	1.32	7.02
	4	2.28	550	2125	4	5	1.75	0.75	21.40	40	1650	800	5.65	0.10	35	120	0.040	1.28	3.86
	5	2.49	1210	1875	14	15	1.80	0.59	20.20	110	4200	1100	7.30	0.13	67	140	0.180	0.45	1.54
	6	2.41	1190	1725	56	58	3.40	2.80	17.00	70	2050	1100	8.20	0.33	65	150	0.370	0.84	1.45
	7	2.91	1050	1975	6	10	1.90	3.05	18.30	50	2200	800	5.20	0.10	55	140	0.085	0.90	1.89
	8	2.79	910	2325	4	5	0.70	0.17	21.70	40	3100	1150	6.00	0.10	50	120	0.050	0.75	2.55
	9	3.62	540	2500	2	5	0.85	0.07	22.20	40	4100	900	5.80	0.17	57	140	0.035	0.69	4.62
	10	2.57	140	2400	2	2	1.05	0.59	22.30	20	950	500	4.55	0.07	15	110	0.005	2.52	17.10
	11	1.83	1060	2275	16	19	0.70	3.50	20.70	40	1000	1150	5.00	0.07	57	120	0.075	2.27	2.15
	12	1.62	1000	2050	20	30	0.85	6.65	16.50	40	650	850	4.55	0.07	32	100	0.040	3.15	2.05
	13	1.97	975	1875	6	9	1.20	6.90	18.00	40	900	1000	4.55	0.30	70	120	0.030	1.88	1.92
	14	0.73	2150	2275	2	3	2.90	9.40	11.70	380	2000	2600	7.95	0.20	130	180	0.085	1.13	1.06
	15	0.38	560	2200	2	7	1.30	0.07	19.50	240	1300	750	6.50	0.10	55	120	0.230	1.69	3.92
	16	1.52	900	2175	2	5	0.85	1.45	20.40	40	700	1300	5.20	0.05	45	120	0.025	3.10	2.42
DR 4	1	1.68	1100	2325	4	5	1.10	0.90	20.60	30	1400	500	4.90	0.17	60	100	0.070	1.66	2.11
	2	1.89	210	1700	2	2	1.60	0.85	19.05	30	800	750	4.50	0.10	15	90	0.015	2.12	8.09
	3	2.28	175	900	2	12	0.76	12.20	14.10	40	400	1450	4.30	0.10	17	60	0.035	2.25	5.40

Table 18. Representative geochemical analyses, canonical sources (B), Ni/Cr and Ni/NiP ratios for komatiite samples from three holes at Dingo Range West.

Although no nickel sulphide mineralization is known, some samples, notably 10-16, hole 3 and 1-3 hole 4 show moderate to strong mineralization coefficients. The samples from holes 3 and 4 represent several thick units and are mainly peridotites. Note the strong negative correlation between Mg and Ca in samples 10 through 16. Nickel remains constant in these samples but Mg appears to have been replaced by Ca.

content. Disseminated pentlandite was noted in both holes 2 and 3 but is not directly correlated with either the NiP or S analyses.

5.2.2 Devines

Devines (Fig. 45) is a minor occurrence of nickel sulphides. The Devine komatiite sequence (volcanic suite) consists of several thick units separated by sedimentary horizons. It has been intruded by irregular quartz porphyry dikes.

At Devines the geological sequence which dips and faces west is (from east to west): metasediments; banded iron formation; komatiite sequence; sequence of mafic rocks with some interlayered ultramafic units; thick sequence of metabasalts.

Several zones of minor nickel sulphide mineralization (up to 3 m grading 1.3% Ni and 0.15% Cu), were encountered within the lowermost komatiite unit. Petrographic examination suggests that a variety of ultramafic rocks are present. Talc-chlorite-tremolite, serpentinite, or serpentinite-talc-chlorite rocks are the most common but several samples showed coarse random spinifex texture and four samples had skeletal olivine texture after olivine peridotite or dunite. Discriminant analyses A and B both classified 81% of samples from Devines as Mineralized. NiP values are relatively high, (mean 1399 ppm) and give rise to low Ni/NiP ratios (mean 1.4). Chromium is also relatively high for a mineralized komatiite (mean 1778 ppm). Geochemical values for individual samples listed in Table 19 illustrate the dependence of canonical score on Ni/Cr ratio and the poor correlation between S and NiP.

5.2.3 Dingo Range East and Lalor North

The Dingo Range East and Lalor North komatiite sequence has a strike

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	S	Ni/Cr	Ni/NiP
102	334	1.71	850	1600	18	17	1.95	0.07	15.20	90	2200	700	7.10	0.07	42	110	0.30	0.73	1.88
	360	2.61	1250	1500	94	94	2.05	0.14	15.60	110	3250	600	7.10	0.17	85	150	0.42	0.46	1.20
	476	2.73	1625	2300	22	22	1.45	1.10	19.90	50	3350	700	5.60	0.17	80	130	0.125	0.67	1.42
	495	2.34	1450	2000	2	5	2.30	0.06	20.50	30	1800	900	6.00	0.20	92	140	0.085	1.11	1.38
	610	2.87	1050	1675	48	80	1.80	3.65	17.20	50	2100	1000	5.50	0.20	65	110	0.08	0.75	1.59
	634	2.04	1275	2100	2	5	1.20	0.11	21.70	50	1750	850	4.60	0.13	57	120	0.05	1.20	1.65
202	651	0.90	1075	2100	2	2	1.35	0.06	22.20	40	1100	650	4.80	0.10	32	100	0.04	1.91	1.95
71	234	2.07	1275	1650	20	21	1.70	1.20	20.10	50	1750	900	6.10	0.10	72	120	0.16	0.94	1.29
78	257	0.80	465	1225	2	2	5.15	0.36	19.30	40	650	1300	4.30	0.25	22	80	0.04	1.88	2.63
69	227	2.04	1350	1900	6	7	1.95	0.88	19.10	40	1500	850	5.70	0.13	87	140	0.135	1.27	1.41
	236	1.08	1725	2100	18	20	2.05	1.10	19.50	80	1500	800	5.70	0.17	82	120	0.20	1.40	1.21
	253	1.40	1875	2325	26	26	1.70	0.74	20.30	60	1600	850	5.70	0.13	90	130	0.19	1.45	1.24
	263	1.80	1825	2250	12	15	1.45	0.23	20.10	30	1400	900	5.10	0.13	82	120	0.145	1.61	1.23
	267	1.61	1475	2000	8	10	1.45	0.27	20.10	30	1150	750	5.60	0.13	80	120	0.17	1.74	1.35
	305	2.10	475	1000	10	11	2.20	7.60	14.20	40	850	1250	5.40	0.13	27	80	0.085	9.40	2.10
96	313	1.27	3350	4000	150	141	6.60	0.41	16.80	80	2500	650	6.90	0.17	110	170	0.94	1.60	1.19

Table 19. Geochemical analyses, canonical scores (B), Ni/Cr and Ni/NiP ratios for komatiite samples from the mineralized, volcanic sequence at Devines. The high canonical scores (Barren) of several samples are caused by either high Cr, low Zn or large differences between CuP and Cu (probably analytical error). Note that Cr is higher in this volcanic sequence than in the intrusive Forrestania sequence.

length in excess of 20 km (Fig. 46), a maximum width of 450 m and an average width of 250 m. The footwall of the ultramafic is finely laminated banded iron formation which is sulphide rich and graphitic in part. At Dingo Range East, the sequence overlying the banded iron formation consists of the following units:

1. Differentiated ultramafic grading from peridotite at the base to a pyroxene rich rock at the top;
2. Metagabbro consisting of amphibole and feldspar grading from more mafic at the base to more felsic at the top;
3. A series of talc, chlorite, tremolite, carbonate, magnetite schists, which are interpreted as representing a series of thin units. At Lalor North the sequence is similar except that the gabbro is missing. A second peridotite member, approximately 2 km in length, has been defined overlying the gabbro in the southern section of Dingo Range East.

Discriminant analysis B classified 100% of samples from Dingo Range East and Lalor North as Barren. The geochemical analyses (Table 20) indicate that some of the komatiites are olivine peridotites and are relatively high in nickel content. One hole, DREP 9 also contains significant NiP values with Ni/NiP ratios of approximately 2. Chromium is high in this hole, however, and based on this point the samples can be regarded as Barren. The main chemical differences between Dingo Range East and Dingo Range West komatiites are the higher values of Cr, Mn and Fe at Dingo Range East.

5.2.4 Mt. Step and Collin Well

The Mt. Step komatiite complex (Fig. 46) forms a structurally complex area of komatiitic rocks with associated gabbroic rocks. Strike faulting may have contributed to the linear, en echelon appearance of the complex.

Map Code	Hole No.	Depth (m)	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	Ni/Cr	Ni/NiP
33	DREP7	61	3.40	500	1850	10	4	2.00	1.10	18.80	50	2400	1200	7.00	0.17	23	130	0.77	3.70
	DREP7	67	3.03	540	1250	30	20	2.80	2.90	16.20	80	2400	1400	7.45	0.40	60	130	0.52	2.31
33	DREP9	64	2.85	1040	2150	13	6	1.60	0.82	20.30	50	2800	1000	7.10	0.15	65	135	0.77	2.06
	DREP9		3.32	925	2100	40	24	1.60	0.75	20.30	70	4300	1150	6.80	0.15	65	140	0.49	2.27
	DREP9		3.26	1040	2150	8	4	1.70	0.82	20.60	80	4150	2150	7.00	0.17	60	160	0.52	2.07
	DREP9		3.09	1040	2000	5	4	1.60	0.78	20.80	70	4100	1700	6.80	0.17	35	140	0.49	1.92
	DREP9	100	3.27	1125	2000	5	4	1.70	1.35	20.30	70	5000	1200	7.00	0.18	30	130	0.40	1.78
33	DREP10	76	3.64	325	1750	8	4	2.30	1.65	18.70	80	4050	1300	7.80	0.26	25	130	0.43	5.38
	DREP10		3.86	325	1575	18	8	2.70	2.80	18.00	80	3800	1450	7.90	0.29	25	130	0.41	4.84
	DREP10		3.54	300	1350	15	8	3.30	3.00	16.00	80	3250	1450	8.05	0.35	38	125	0.42	4.50
	DREP10	98	2.84	365	1125	40	28	4.00	6.30	12.70	150	2650	2100	9.20	0.44	35	115	0.42	3.08
31	LNP7	69	3.32	300	1750	14	18	1.85	1.50	18.20	60	3200	1100	6.60	0.12	38	115	0.55	5.83
	LNP7		3.79	250	1650	14	25	1.70	2.30	16.20	50	2750	1450	6.50	0.17	35	115	0.60	6.60
	LNP7		3.71	200	1525	24	28	1.50	2.50	17.30	50	2550	1500	6.70	0.17	30	115	0.60	7.62
	LNP7		3.79	215	1600	16	25	1.85	3.10	16.90	60	2850	1400	6.60	0.28	28	110	0.56	7.44
	LNP7	100	3.78	240	1750	28	33	1.70	2.30	18.40	60	3300	1200	7.00	0.18	28	125	0.53	7.29
31	LNP8	76	2.67	465	1425	46	58	1.70	2.30	17.55	40	1050	1300	7.80	0.21	48	135	1.36	3.06
	LNP8		3.14	215	1300	32	35	2.20	3.35	16.50	40	1200	1400	7.60	0.21	33	130	1.08	6.04
	LNP8	92	3.25	475	1600	24	33	2.10	2.80	18.00	30	1750	1250	7.10	0.20	43	120	0.91	3.37
31	LNP9A	82	3.46	350	1650	30	33	1.60	1.65	18.00	30	1800	1150	6.25	0.17	33	120	0.92	4.70
	LNP9A		3.29	275	1800	18	25	1.85	1.65	19.30	40	1900	1000	6.60	0.18	30	125	0.95	6.54
	LNP9A	98	3.19	250	1700	30	38	1.80	1.60	18.80	40	1700	1008	6.80	NA	28	120	1.00	6.80
31	LNP10	95	3.68	350	1575	33	38	1.80	2.60	17.60	40	2550	1800	6.40	NA	28	110	0.62	4.50
	LNP10		3.45	500	1600	19	25	1.80	2.30	17.40	30	2100	1200	6.30	NA	35	110	0.76	3.20
	LNP10	107	3.68	500	1500	30	33	1.90	2.50	17.20	30	2400	1300	6.40	NA	33	110	0.63	3.00

Table 20. Representative geochemical analyses, canonical scores (B), Ni/Cr and NiP ratios for barren komatiite samples from seven rotary holes at Dingo Range East and Lalor North. Most holes are obviously Barren, with relatively low NiP and Ni (thus very high Ni/NiP ratios) high Cr (low, less item 1, Ni/Cr ratios). However Hole Drep 9 has NiP values and Ni/NiP ratios in range normally considered Mineralized. In addition the komatiite is peridotitic. It is placed in the Barren category because of very high Cr results. These samples are all 3.1 m., drill chip composites.

Discriminant analyses A and B classified 100% of samples as Barren. Geochemically (Table 21) the komatiites are low in NiP, Ni and Mg, although most samples were probably originally peridotites. Cr, Mn, Fe and TiO_2 are all high relative to mineralized peridotites. This komatiite sequence is unlikely to host nickel sulphide deposits.

The Collin Well area includes several separate komatiite sequences (volcanic suite). The northern sequence at Collin Well North appears to be intrusive into mafic volcanics and the southern komatiites are probably thin units. High Mg basalts have been noted associated with the eastern-most komatiite at Collin Well. Detailed geological knowledge is restricted to the Collin Well North komatiite. Diamond core drilling indicated that the sequence here is as follows (Fig. 49):

1. The uppermost unit stratigraphically is a series of mafic igneous rocks which in clude meta-basalts and their intrusive equivalents. These rocks contain minor amounts of chalcopyrite, pyrite and bornite.
2. The second unit is a komatiite sequence (mainly talc-carbonate-serpentine) intruded by gabbro. Olivine pseudomorphs can be discerned, particularly towards the base of the unit. Chromite and magnetite are common accessories and trace amounts of millerite-violerite were noted in several specimens. The total sulphide content does not exceed 0.5%. The gabbro contains minor chalcopyrite, pyrrhotite and marcasite.
3. The basal unit consists of banded to massive quartz biotite-muscovite schists. The felsics form 60% to 70% of the rock by volume and the matrix is mainly potash feldspar. This unit is possibly of acid volcanic origin.

Six spot core samples were obtained from one core hole at Collin Well North (Fig. 49) and eight samples of drill chips were obtained from three

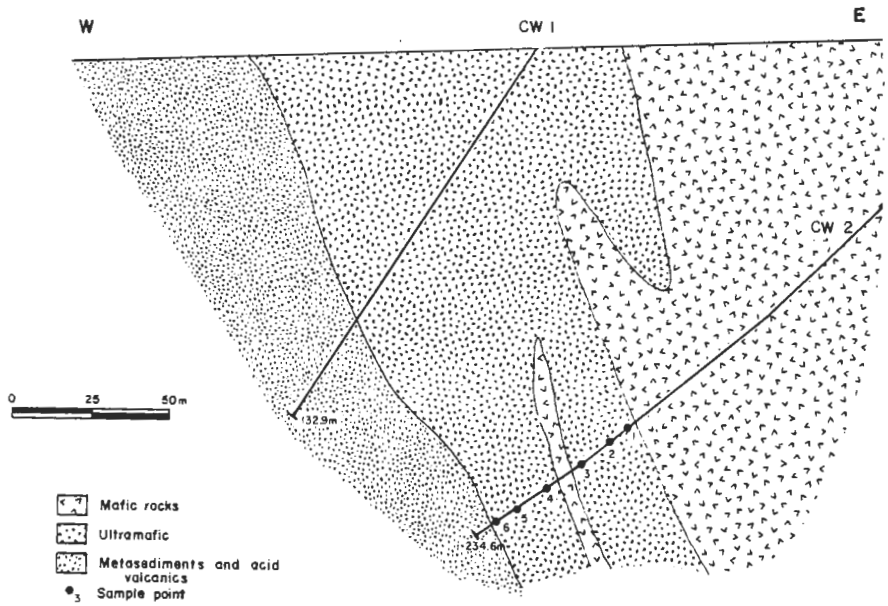

Fig. 49 . Geological Cross Section, drill holes 1 and 2, Collin Well North showing location of core samples

rotary holes. Discriminant analyses A and B both classified 100% of samples as Barren. Chemically (Table 21) the rocks are mainly peridotites, with pyroxenites and pyroxene peridotites in hole CWW7.

The Collin Well West komatiites are lower in Ni and higher in Cr, Mn and Fe than the Collin Well North komatiites. Although trace millerite and violarite are present in hole CW2, total S and Ni/P results are low.

Hole No.	Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	S	Ni/Cr	Ni/Nip
MSP6	30	100-110	3.78	200	1400	19	28	2.10	2.85	16.60	40	2050	1250	7.00	0.34	20	110	ND	0.68	7.00
MSP6		170-180	3.99	150	1300	18	28	2.70	3.10	15.70	50	2300	1300	7.20	0.39	15	110	ND	0.57	8.67
MSP6		270-280	3.86	240	1125	63	80	2.80	4.00	15.50	50	2550	450	8.00	0.44	25	110	ND	0.44	4.69
MSP6	95	300-310	3.63	225	1125	53	55	3.15	3.70	15.10	70	2750	1350	7.90	0.47	20	105	ND	0.41	5.00
MSP7	27	90-100	4.44	125	1600	8	13	1.20	0.43	20.30	30	3000	950	7.20	0.18	23	125	ND	0.53	12.80
MSP7		150-160	4.10	225	1100	34	35	0.95	1.60	18.60	40	2500	2450	8.30	0.16	35	120	ND	0.44	4.89
MSP7	67	210-220	4.60	90	1200	24	35	1.35	2.30	17.40	30	2250	1900	8.30	0.23	23	115	ND	0.53	13.33
MSP8	43	140-150	3.07	300	1200	48	50	3.15	2.15	15.90	100	2650	1350	6.80	0.48	28	110	ND	0.45	4.00
MSP8		170-180	3.48	300	1200	21	28	3.30	2.60	15.70	60	2650	1300	7.60	0.48	28	110	ND	0.45	4.00
MSP8		200-210	4.04	165	1050	5	10	3.15	4.30	15.30	50	2300	1300	7.60	0.52	18	110	ND	0.46	6.36
MSP8		230-240	4.06	150	1225	8	15	3.05	3.80	16.10	50	2500	1300	7.10	0.39	18	110	ND	0.49	8.17
MSP8		260-270	4.02	215	1175	9	13	1.80	4.00	16.30	40	2450	1400	7.10	0.28	28	110	ND	0.48	5.46
MSP8	88	280-290	4.07	315	1100	10	15	1.25	5.30	16.30	30	2050	1300	7.10	0.16	33	110	ND	0.54	3.49
CW2	175	573	3.79	660	1700	2	5	1.10	5.20	17.00	30	2500	1100	5.35	0.17	43	120	0.085	0.68	2.58
		600	2.99	650	1775	2	5	1.05	4.00	18.80	40	1650	700	4.20	0.09	43	110	0.065	1.08	2.73
		637	3.86	700	1500	8	12	1.60	4.10	17.40	30	2600	800	4.40	0.17	40	110	0.055	0.58	2.14
		680	3.30	560	1825	4	6	0.86	1.40	19.25	40	2400	900	4.60	0.07	35	110	0.040	0.76	3.25
		720	3.78	60	2250	2	2	0.45	0.95	21.70	30	1600	600	4.00	0.07	5	100	0.005	1.41	37.50
	226	742	3.20	50	1400	6	4	4.30	2.65	17.20	30	1000	300	5.35	0.30	5	90	0.015	1.40	28.00
CWNP2	58	190	3.26	300	1900	2.5	5	0.95	0.83	20.00	20	1600	650	5.50	0.08	38	100	ND	1.19	6.33
CWNP2		240	3.65	175	2000	2.5	5	1.05	0.55	21.00	20	1700	600	5.20	0.06	18	100	ND	1.18	11.42
CWNP2	88	290	3.12	165	1800	8	10	1.55	1.45	17.40	30	1450	700	5.20	0.15	20	100	ND	1.24	10.91
CWWP6	37	120	3.77	425	1200	15	20	1.65	1.15	19.00	80	4100	1500	9.10	0.24	68	150	ND	0.29	2.82
CWWP6		140	4.28	200	800	11	23	2.10	2.15	17.40	70	2700	1700	9.00	0.28	53	145	ND	0.30	4.00
CWWP7		120	3.67	300	1000	45	58	3.50	3.80	14.70	80	3200	1450	8.70	0.53	33	110	ND	0.31	3.33
CWWP7		150	3.76	325	1075	70	73	3.60	4.70	14.10	60	3100	1400	8.70	0.55	35	110	ND	0.35	3.30
CWWP7	52	170	3.64	325	975	64	75	3.70	4.70	14.30	70	2800	1400	8.50	0.57	35	110	ND	0.35	3.00

Table 21. Representative komatiite sample results from one core hole and six rotary holes at Mt. Step (MS) and Collin Well (CW). Most of the samples are low in NiP and Ni, have high canonical scores and are high in Cr, and are thus Barren. Some peridotite samples (hole CWNP2) have moderate to low Cr and would be considered Mineralized except for very low NiP (and thus S).

5.3 DISCUSSION

The Wonganoo-Bandjawarn greenstone belt has been intensively prospected for nickel sulphides using geology, geochemistry and geophysics. A large number of drill holes were completed.

The exploration suggested that one area, Devines, contained small accumulations of nickel sulphides but that all other komatiites were Barren. The discriminant analysis results generally supported these conclusions although Dingo Range West, as has been pointed out above, exhibited some characteristics of a mineralized sequence.

The Dingo Range West sequence is a good example of several well differentiated thick unit komatiites separated by interflow sulphide rich sediments. There are no thin units present in the sequence. Small amounts of disseminated sulphide, pyrrhotite, pyrite and pentlandite are fairly common throughout the ultramafics. The main conclusion reached after a study of the geology and geochemistry is that the Dingo Range West sequence consists predominantly of thick unit komatiites which have a relatively low overall mineralization coefficient. This could be interpreted to mean that nickel sulphides were generated by the komatiite magma and thus nickel sulphides could occur in the sequence but probably some distance from the drill holes sampled. Alternatively the komatiite magma may have generated only small quantities of nickel sulphides.

Devines, as expected, has well defined geochemistry indicative of a mineralized komatiite. The geochemical results from the remaining areas in this greenstone belt all indicate that the komatiites in question are Barren. Dingo Range East is an interesting example where some of the komatiites have relatively high Mg, Ni and NiP but are still regarded as Barren because of a high Cr content. Mt. Step komatiites are examples of peridotites with relatively low Ni and NiP and high Cr, Mn and Fe.

As already noted the Wonganoo-Bandjawarn greenstone belt was intensely prospected using conventional methods such as geological mapping, aeromagnetics, extensive surface and drill hole geochemistry and numerous drill holes. The same results could be achieved using the criteria developed in this study at a much reduced exploration cost. Exploration need only consist of an aeromagnetic survey, followed by minimal geological mapping and sufficient drill holes to obtain 20-30 unweathered samples of komatiite from each main komatiite sequence. The komatiite geochemistry would have indicated that the Devines and Dingo Range West areas were of interest but the remaining areas were Barren. Detailed exploration could have concentrated on these areas instead of covering the whole greenstone belt.

CHAPTER 6

6. COMPARISON OF FORRESTANIA NICKEL PROVINCE WITH THE CONTIGUOUS SOUTHERN CROSS GREENSTONE BELT

This chapter describes the trace and major element geochemistry of komatiite ultramafics from throughout the Southern Cross-Forrestania greenstone belt (Fig. 50). This greenstone belt is a continuous north, northwest trending segment of Archaean volcanics and sediments surrounded by granitic rocks. Substantial deposits of nickel sulphides are associated with intrusive suite komatiites at Forrestania but only very small deposits are known in the central and northern parts of the belt. Komatiites are widespread in the latter parts of the belt but it will be shown that they are significantly different chemically from komatiites in the Forrestania Nickel Province.

The study of the Southern Cross part of this belt (Fig. 51) was initiated as part of a nickel sulphide exploration program. Exploration was severely hindered by poor outcrop, deep oxidation and surface leaching, extensive areas of transported soils and thick laterite profiles. Laterite is extensive. Ultramafic rocks rarely outcrop except as rubbly exposures between hills of more resistant mafic rocks or adjacent to salt lakes where recent erosion has stripped off some of the surface weathered material.

Exploration was carried out in two phases:

1. In the first phase all ultramafics were roughly defined using geological reconnaissance, aeromagnetic data and geochemical soil samples.

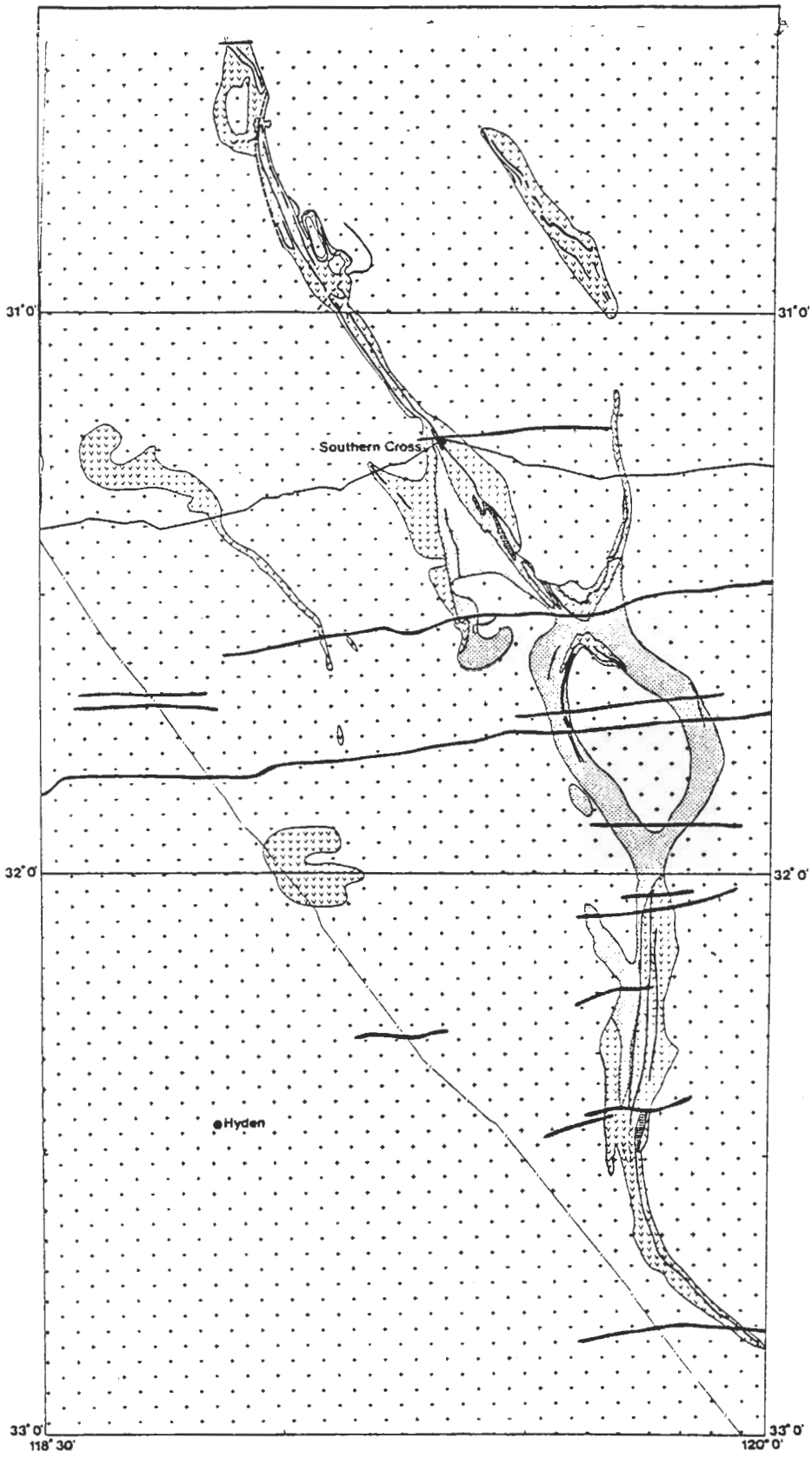

FIGURE 50: Geology of Southern Cross - Forrestania greenstone belt.

2. In the second phase fresh samples of ultramafic from komatiite sequences throughout the belt were obtained to determine the nickel sulphide potential of the belt and to compare these komatiites with known nickel sulphide hosts at Forrestania. Samples were obtained from prospects which had been previously drilled and from drill holes drilled for this specific purpose. Wherever possible the higher Mg or peridotitic sections of komatiite sequences were sampled.

Exploration was not successful in that no new nickel sulphide deposits were encountered but evaluation of the komatiite geochemical data indicated that the Southern Cross part of the belt was unlikely to contain major deposits of nickel sulphides.

6.1 FORRESTANIA NICKEL PROVINCE

The Forrestania Nickel Province (Fig. 2) contains a group of nickel occurrences (includes Cosmic Boy and Digger Rocks) in a komatiite sequence, near the southern end of the Southern Cross subprovince (Williams, 1973). Specific details of the number, size and grade of occurrences are not available, but it is known that some occurrences are of grades normally regarded as ore. It is probable that the area will be a major producer of nickel sulphides at some time in the future. The mineralized komatiites and the nickel sulphide deposits are considered to be members of the intrusive suite.

The volcanic and sedimentary succession at Forrestania occupies a long narrow north-south trending belt, between 5 and 15 km wide, bounded on both sides by granite gneiss. The succession is strongly deformed and highly metamorphosed which, together with almost total absence of surface outcrop, makes stratigraphic and structural interpretation extremely difficult. The major lithologies present include:

1. Olivine rich komatiites with horizons of disseminated nickel sulphide at contacts and wholly within individual units. The main zone of mineralized komatiites is comparatively homogeneous, uniform in composition with high Mg and low Al and Ca. There is no evidence of former spinifex zones which would reflect a silicate liquid magma fraction. Most of the olivine is forsterite of metamorphic origin but possible igneous olivine relicts have been noted. The main komatiitic horizon is linear and semi-continuous and appears to have escaped folding exhibited by adjacent rocks.
2. Foliated metasediments with most sedimentary textural features obliterated. The original rock types were laminated siltstones, shales

and greywackes. Acid volcanics could be present but would have been rendered unrecognizable because of the degree of reconstitution. Metamorphic grade based on sediment mineralogy is mid to upper amphibolite facies.

3. Banded iron formation, now mainly finely laminated quartz magnetite rocks occur east of the main komatiite zone.

4. Mafic volcanics now coarse-grained amphibolites are subordinate which is in contrast to Kalgoorlie-Norseman Nickel Province.

At Cosmic Boy (holes 1 and 2), sulphide mineralization occurs at contacts between intrusive komatiites and metasedimentary rocks, particularly oxide facies banded iron formation. It also occurs within komatiite units and in thin slivers of ultramafic rock within metasedimentary units. The sulphides occur in bladed olivine-talc rocks which have been partly reserpentinized. The talc is interstitial to the olivines. There is a tendency for the proportion of pyrrhotite to increase with an increase in the total sulphide content towards the contact of the mineralized zone with metasedimentary rocks. At Digger Rocks, approximately 17 km south of Cosmic Boy, massive sulphides and disseminated sulphides occur within a komatiite sequence which is at least 300 m thick.

The geochemistry of Forrestania komatiites has already been described in Section 4.2.2. These komatiites form a distinctive group (Fig. 5) with close affinities to the Queen Victoria Rocks komatiites. Nickel (mean 1980 ppm) and Mg (24.0%) are higher than the means for mineralized ultramafics (Table 3) and Cu (24 ppm), Al (0.4%) and Cr (1076 ppm) are significantly lower. Mean Ni/Cr ratio is 2.8, Ni/Ni$\underline{P}$ ratio is 2.2 and Ni/Mg ratio is 84.

The homogeneous nature of Forrestania komatiites is illustrated by the geochemical results for holes 4 and 5 (Figs. 42 and 43 and Table 16). In addition these komatiites have a relatively consistent geochemical signature over a strike length of at least 30 km and perhaps as much as 60 km.

6.2 SOUTHERN CROSS GREENSTONE BELT

The Southern Cross greenstone belt extends from 20 km south of Marvel Lock to the Trough Wells area in the north (Fig. 51). The greenstone belt continues south and joins the Forrestania Nickel Province. The Southern Cross belt contains the following areas which are described in this study: Marvel Lock A, Marvel Lock B, Marvel Lock C, Southern Cross drill holes, Bullfinch, Ennuin and Trough Wells. Marvel Lock A and Trough Wells were classified as Mineralized for the statistical analysis and the remaining were classified as Barren. Southern Cross drill holes is a grouping of samples from 17 drill holes designated SXP1 to SXP15 and DDH1, DDH4, DDH5 (Fig. 51).

There is no recently published geological data on the Southern Cross greenstone belt but earlier workers refer to two rock associations. The dominant association consists of metabasalt, mafic tuffs, ultramafic rocks, anthophyllite schist, dolerite and banded iron formations. The other is a metasedimentary association consisting of phyllite, greywacke, chert, banded iron formation and conglomerate, together with various metasedimentary schists. Felsic volcanics appear to be relatively rare. According to Williams(1974), the configuration of this greenstone belt is a result of the emplacement of granitic bodies.

The main komatiite sequences and banded iron formations (Figs. 28 and 52) were defined from geological traverses, geochemical soil sample results and interpolating using aeromagnetic data. Outcrop is poor and often restricted to linear ridges of banded iron formations. The greenstone belt varies from less than 1 km in width, to a maximum width of 10 km north of Southern Cross. The komatiites include both volcanic suites such as at Trough Wells (Section 4.1.3) and Ennuin and intrusive suites, but in general little is known of the detailed composition of most komatiites. Banded iron formations tend to be strongly magnetic and individual formations have been

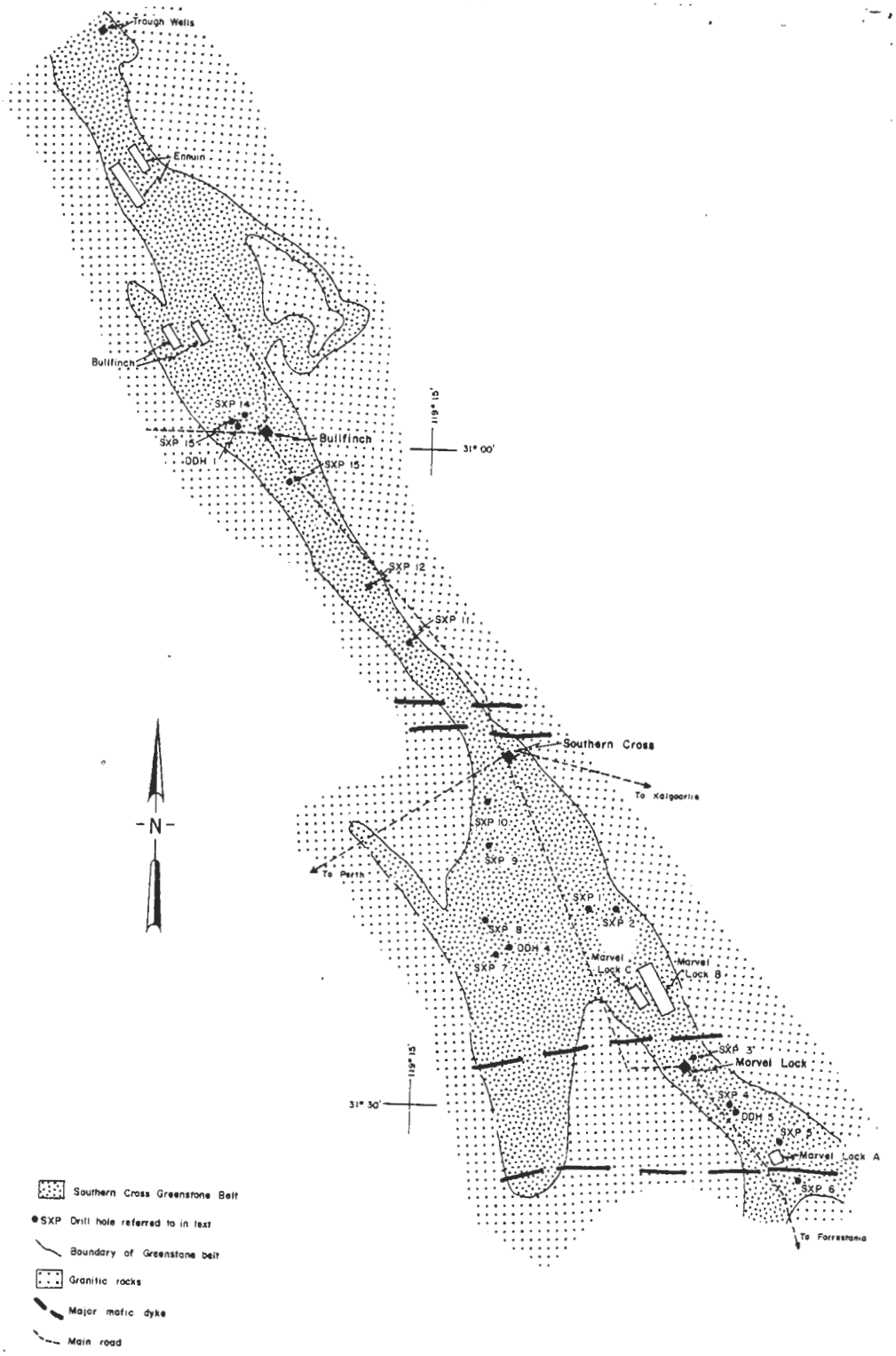

Fig. 51. Southern Cross Greenstone Belt showing location of areas described in text.

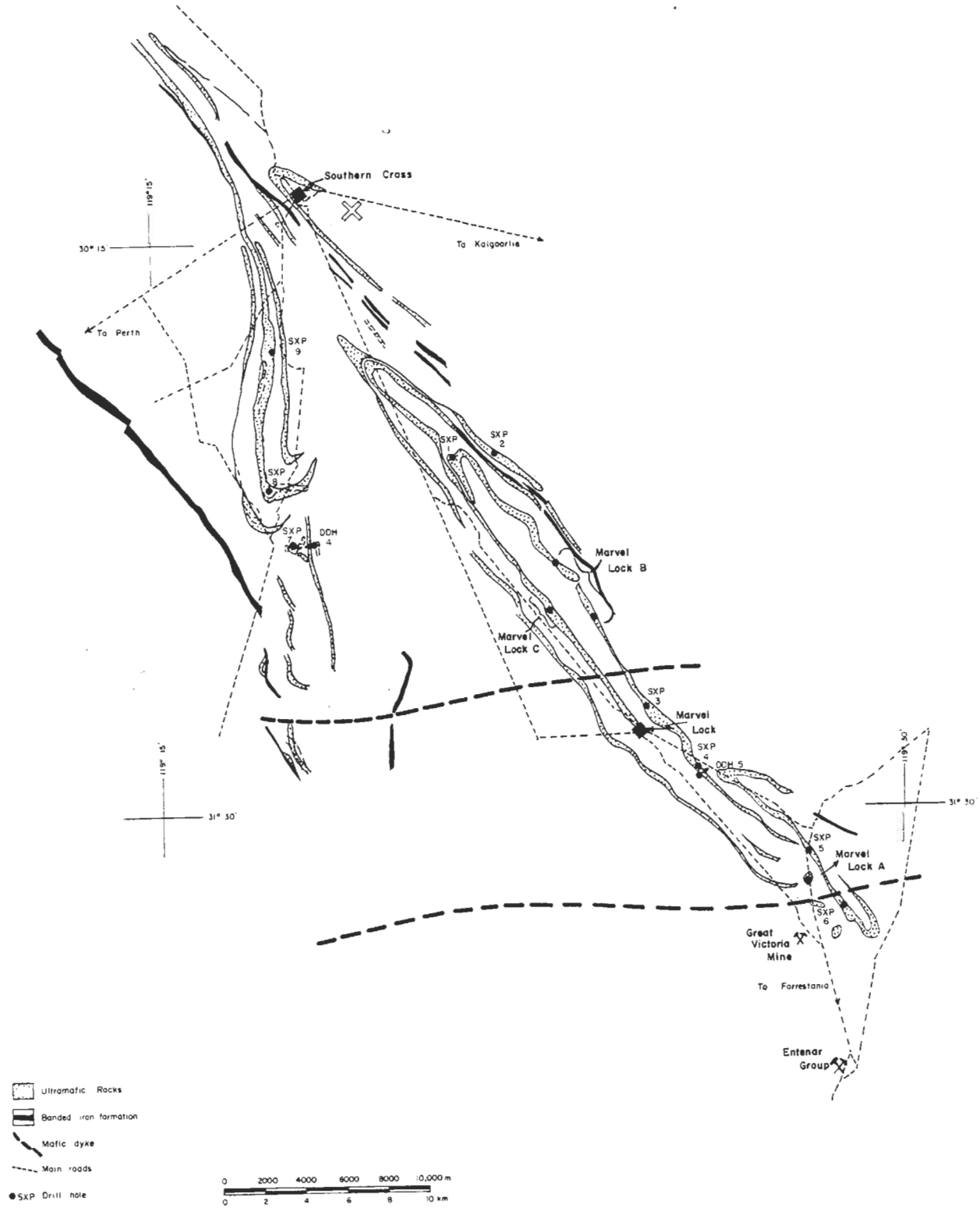

Fig. 52. Interpretive partial geological plan of the southern part of the Southern Cross greenstone belt showing ultramafic sequences, banded iron formations and location of areas sampled.

traced over long distances. Nickel sulphide mineralization is relatively uncommon throughout the entire belt and is restricted to occurrences at Marvel Lock A and Trough Wells (both described in this study) and near Southern Cross.

6.2.1 Marvel Lock A

The Marvel Lock A (Fig. 52) komatiite contains significant nickel sulphides which were intersected in several core drill holes. Eighty samples were obtained from two core holes but only 43 were used in the statistical analysis. All samples were spot core selected mainly at 3.1 m intervals and analyses from one hole are listed in Table 22. The komatiites in both holes were logged mainly as serpentinite, with some talc-carbonate alteration and minor zones of talc-amphibolite. Bladed olivine textures, probably of metamorphic origin, have been noted. Graphitic, pyrrhotitic shales are present between 140 and 170 m (Table 22) and between 167 and 170 m the rock contains between 30% and 70% sulphide, mainly pyrrhotite. Between 1% and 3% sulphides are common in the komatiite over widths of 50 to 80 m. Pyrrhotite-pentlandite ratio varies between 2:1 and 6:1. Near Marvel Lock A the greenstone belt is intruded by an east-west mafic dyke which does not outcrop but is prominant in the aeromagnetic data.

Mean geochemical values for the komatiites include relatively high NiP (1691 ppm) and Cu (89 ppm) values (Table 3) but most other results approximate the means for all mineralized komatiites. Discriminant analysis A (Table 4) classified 75%, and analysis B, 84% of samples as Mineralized. Mean Ni to Cr ratio is 1.4 and Ni to NiP ratio is 1.2 Some transfer of nickel from the ultramafic to the overlying sulphide sediment has occurred and the basal 7 m of sediment now contains approximately 1200 ppm Ni. The magnesium results in Table 22 suggest that the Marvel Lock A komatiite is a homogeneous, intrusive komatiite, originally of dunitic composition.

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	Ni/Cr	Ni/Nip
167	459	ND	163	225	199	218	4.88	0.20	0.92	1000	450	800	6.60	0.25	48	100	ND	ND
	461	ND	163	300	100	223	7.45	0.58	0.92	830	450	1000	6.30	0.51	38	55	ND	ND
	468	ND	100	125	190	175	5.85	0.36	1.05	460	450	700	8.80	0.35	25	55	ND	ND
	480	ND	185	225	313	348	5.70	0.86	1.20	310	400	1250	7.60	0.31	30	60	ND	ND
	486	ND	238	275	238	258	5.85	0.47	1.25	840	500	950	8.60	0.25	33	60	ND	ND
	500	ND	38	75	43	48	5.45	1.05	1.25	170	350	750	2.20	0.31	18	48	ND	ND
	510	ND	400	475	813	980	4.80	0.83	1.00	2450	300	2200	16.80	0.14	100	210	ND	ND
	521	ND	250	325	413	450	4.40	0.66	0.99	370	250	1050	11.00	0.46	346	1000	ND	ND
	530	ND	450	500	975	1125	6.25	1.25	1.08	990	300	1150	14.70	0.26	58	168	ND	ND
	547	ND	188	225	98	198	7.25	0.60	0.99	670	550	400	4.00	0.65	35	65	ND	ND
167	548	ND	468	825	438	625	6.52	0.04	0.14	10	200	350	52.00	0.03	155	825	ND	ND
	551	ND	350	450	448	600	8.40	0.17	0.98	1000	550	900	18.00	0.15	28	55	ND	ND
	553	ND	598	1200	488	725	1.55	0.02	1.70	150	200	1850	51.50	0.10	54	100	ND	ND
	556	ND	550	1150	1913	3000	1.20	0.01	0.53	300	156	1400	49.50	0.03	50	100	ND	ND
170	560	ND	1150	1400	75	98	0.85	11.20	14.00	40	1150	1550	5.80	0.04	63	115	ND	ND
	570	2.29	775	950	213	243	1.70	0.83	15.20	80	2300	700	6.20	0.27	50	70	0.41	1.22
	580	1.84	1700	2175	8	13	0.57	0.11	25.00	40	1500	1300	7.50	0.07	95	145	1.45	1.28
	590	1.27	2500	2800	21	28	0.87	0.06	24.40	40	1500	850	7.80	0.13	130	155	1.93	1.16
	600	1.90	2300	2650	313	350	0.62	0.04	22.20	40	1450	550	6.90	0.10	110	145	1.83	1.15
	610	1.64	2150	2500	225	258	0.81	0.05	22.80	40	1550	450	8.30	0.10	108	145	1.61	1.16
	620	1.68	2350	2725	68	80	0.91	0.02	22.80	40	1750	1050	7.10	0.10	105	145	1.56	1.16
	630	1.39	1650	2200	83	100	0.67	0.06	24.80	40	1150	1250	7.40	0.10	78	125	1.91	1.33
	640	0.71	825	1300	39	48	0.10	0.33	23.60	40	300	1900	5.80	0.03	48	95	4.33	1.58
	650	ND	2200	2600	400	450	0.74	0.04	24.40	40	1650	1700	7.30	0.10	113	160	1.58	1.18
	660	ND	2200	2600	438	475	0.77	0.05	23.80	40	1600	1400	7.00	0.16	113	180	1.62	1.18
	670	0.94	2000	2400	213	248	0.54	0.05	25.00	40	850	1450	7.00	0.02	113	130	2.80	1.20
	680	1.32	2000	2575	98	113	0.75	0.03	25.30	40	1250	1400	6.10	0.10	105	135	2.06	1.29
	690	1.97	1725	2400	275	318	0.84	0.02	22.60	40	1750	550	5.70	0.13	73	125	1.37	1.39
	700	1.63	2150	2850	250	283	0.79	0.02	23.40	40	1550	600	6.70	0.12	95	145	1.84	1.33

Table 22. Representative komatiite sample results from a single drill hole at Marvel Lock A, including analyses, some canonical scores (B), Ni/Cr and Ni/NiP ratios. Marvel Lock A komatiites are associated with a minor nickel sulphide accumulation. The komatiite is a homogeneous, high NiP (S), Ni, and Mg ultramafic with moderate Cr. Fe is higher than in most ultramafic with moderate Cr. Fe is higher than in most mineralized komatiites and Cu values are very high. Above the ultramafic (at 170 m.) is a thick, sulphidic sediment sequence. Note that significant Ni has diffused into these sediments for a distance of 3 to 5 m. The extremely high Cu in the komatiite could also be interpreted as diffusion in the opposite direction, but the sharp cut-off in Zn at the contact. with only low Zn in the ultramafic, would suggest that diffusion did not operate in this direction.

6.2.2 Trough Wells

Trough Wells komatiites were described in Section 4.1.3. These komatiites are typical of the volcanic suite with well developed peridotitic thick units and spinifex textured thin units. The peridotitic units have geochemistry typical of mineralized thick units - Ni/Cr ratios greater than 1, Ni/NiP ratios of 1.3 to 2.5 and Ni/Mg ratios greater than 100.

6.2.3 Southern Cross Drill Holes

Southern Cross drill holes is a grouping of 17 drill holes as indicated on Figs. 28 and 52 and other miscellaneous samples from throughout the Southern Cross greenstone belt. Metamorphic grade varies from upper greenschist to high amphibolite and most komatiites retain little in the way of original textures. The core samples were spot core samples taken at 3.1 m intervals and the rotary hole samples each represent a 1.6 or 3.1 m interval of komatiite. Discriminant analysis A classified 87% and analysis B, 86% of samples as Barren (Table 4). Mean Ni to Cr ratio was 0.6 and Ni to NiP ratio was 3.3. Although only 14% of samples were classified Mineralized, most of these samples were from two holes only and thus the classification as Mineralized may be significant.

Hole SXP1 (Table 23A) is a barren peridotitic komatiite and has a very low Ni/Mg ratio. SXP2 is similar in Ni and Cr content to SXP1 but is mainly pyroxenitic in composition. SXP3 is peridotitic and contains more Ni than hole 1 but has higher Cr with resulting low Ni/Cr ratio. Ni/Mg ratio is also relatively low. SXP4 is a high Cr, low Ni pyroxenite. SXP5 is peridotitic in composition with moderate Ni and high Cr. Holes 1 to 5 show no evidence of nickel sulphide potential.

Hole No.	Depth Meters	Depth Feet	Canonical Score	Nip	Ni	Cup	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	Ni/Cr	Ni/NiP
1	64	210-220	3.36	350	1100	8	13	0.92	0.85	17.20	30	1500	850	5.40	0.13	55	105	0.73	3.14
		220-230	3.12	363	1200	9	13	0.81	0.77	18.10	40	1450	950	5.10	0.13	53	115	0.83	3.30
		230-240	3.65	338	1100	9	15	0.81	1.05	18.20	30	1350	950	4.40	0.13	48	115	0.81	3.25
		240-250	2.87	413	1175	13	20	1.05	1.20	17.00	40	1250	950	6.00	0.16	48	110	0.94	2.84
		250-260	3.25	350	1325	3	8	1.02	0.85	18.50	40	1350	950	5.70	ND	40	125	0.98	3.78
		260-270	3.41	363	1325	3	8	1.07	0.66	19.00	30	1350	950	5.70	ND	45	125	0.98	3.65
		270-280	3.29	400	1400	3	8	1.10	0.49	18.50	40	1550	950	6.00	ND	53	135	0.90	3.50
	88.4	280-290	3.62	363	1325	2.5	8	1.70	0.48	19.50	30	1650	850	5.00	ND	43	115	0.80	3.65
2	58	190-200	4.00	235	925	54	78	1.20	7.40	7.90	60	1650	1100	8.60	0.55	35	100	0.56	3.94
		200-210	3.59	400	1000	75	88	1.10	8.30	7.70	70	1500	1700	6.80	0.55	50	110	0.67	2.50
		210-220	3.75	300	950	70	98	1.60	6.80	8.10	90	1800	1450	7.30	0.62	45	115	0.53	3.33
		220-230	3.48	375	1025	29	35	1.35	6.00	8.10	70	1700	1100	6.60	0.61	48	110	0.60	2.73
		230-240	3.17	500	1175	43	55	1.35	7.00	9.30	80	1800	1500	7.40	0.58	60	115	0.65	2.35
		240-250	3.05	538	1125	36	48	1.00	7.60	7.70	70	1350	1150	6.30	0.52	60	105	0.83	2.09
		250-260	3.66	438	825	103	148	1.10	9.10	9.90	70	1600	1550	7.30	0.68	48	105	0.52	1.88
		260-270	2.97	513	1125	48	68	1.10	7.85	11.40	70	1500	1100	6.80	0.67?	53	105	0.75	2.19
		270-280	3.28	338	925	73	80	1.35	7.10	11.60	80	1700	1400	6.80	0.67	43	105	0.54	2.74
		280-290	3.37	413	975	44	73	1.20	8.20	11.80	70	1650	1400	7.10	0.58	48	105	0.59	2.36
	91.5	290-300	3.48	400	1025	54	60	1.20	6.60	9.50	70	1700	1350	6.70	0.60	53	115	0.60	2.56
3	70	200-210	3.56	288	1925	13	28	1.00	0.85	18.50	40	1850	750	5.40	0.14	20	115	1.04	6.68
		210-220	3.68	450	2075	13	23	0.84	0.55	19.30	50	3150	850	6.60	0.19	30	130	0.66	4.61
		220-230	3.21	413	1275	9	10	0.55	1.70	18.50	40	1750	1250	5.00	0.08	35	100	0.73	3.09
		230-240	2.95	588	1675	15	23	0.70	1.20	19.10	50	1750	1050	6.30	0.10	43	125	0.96	2.84
		240-250	3.66	588	1750	9	15	0.94	1.20	18.60	50	3450	900	6.00	0.11	43	120	0.51	2.98
	79.3	250-260	4.46	400	1425	3	10	0.84	1.25	18.20	40	3650	1050	4.50	0.08	35	100	0.40	3.56
4	70	200-210	4.07	225	1075	66	90	2.35	2.05	14.80	100	3050	1450	7.80	0.42	33	140	0.35	4.79
		210-220	4.23	150	975	66	88	2.35	2.60	14.40	110	3100	1400	7.90	0.49	23	130	0.31	6.50
		220-230	3.84	263	975	63	68	2.35	2.40	13.10	100	3050	1500	8.20	0.49	40	130	0.32	3.71
		230-240	4.15	163	975	51	78	2.50	2.60	13.80	100	3050	1200	7.60	0.49	25	120	0.32	5.98
	76.2	240-250	4.26	100	950	46	53	2.60	2.45?	14.20	100	3050	1300	7.60	0.51	18	120	0.31	9.50
5	518	170-180	3.05	775	2000	21	33	1.20	0.78	18.90	110	4250	1500	7.30	0.24	43	130	0.47	2.58
		180-190	2.65	925	2075	30	38	1.20	0.95	18.20	100	3050	1350	7.40	0.20	38	130	0.68	2.51
		190-200	3.14	563	1725	15	23	1.20	0.95	18.20	100	3600	1450	7.80	0.19	39	130	0.48	3.06
		200-210	3.15	375	1500	10	15	1.20	1.05	17.80	90	2900	1500	7.60	0.23	28	120	0.52	4.00
		210-220	2.81	513	1750	15	20	1.35	1.00	18.50	90	2800	1300	7.40	ND	33	125	0.63	3.41
		220-230	3.37	375	1600	5	10	1.35	1.05	18.50	90	3300	1150	6.20	ND	28	120	0.48	4.27
		230-240	4.20	238	1475	2.5	8	1.45	1.40	18.20	90	3700	1250	6.20	ND	18	115	0.40	6.20
	76.2	240-250	4.03	288	1550	4	13	1.20	0.94	19.00	90	3800	1200	7.60	ND	25	135	0.41	5.38
6	70	230-240	2.76	500	2050	2.5	5	0.91	0.32	20.00	40	1500	950	5.60	ND	30	125	1.37	4.10
		240-245	2.63	575	2075	2.5	5	1.05	0.25	19.00	40	1550	950	5.40	0.14	33	120	1.34	3.61
		260-270	2.62	525	2000	2.5	5	0.94	0.44	18.00	40	1400	950	5.90	0.16	40	130	1.43	3.20
		270-280	2.54	575	1950	2.5	5	0.98	1.20	18.10	40	1350	900	5.90	0.14	35	115	1.44	3.39
		280-290	2.69	575	1975	2.5	10	1.00	0.38	18.80	40	1400	600	6.20	0.18	40	110	1.41	3.43
	91.5	290-300	2.12	600	1950	9	18	1.10	0.52	16.00	70	1800	600	7.00	0.22	38	105	1.08	3.25
7	76.2	250-260	ND	200	1250	8	18	1.45	1.80	14.60	100	3400	1450	8.00	0.33	25	125	0.37	6.25
		260-270	3.97	175	1125	9	18	1.60	2.05	14.60	100	3000	1400	7.40	0.41	23	120	0.38	6.42
		270-280	4.38	225	1250	9	18	1.45	2.05	14.60	100	3200	1750	8.20	0.33	103	210	0.39	5.56
		280-290	4.10	198	1200	5	15	1.45	1.80	14.60	100	3150	1500	8.00	0.32	25	125	0.38	5.38
	91.5	290-300	4.19	163	1200	4	13	1.45	1.70	14.20	110	3300	1500	8.00	0.33	18	120	0.36	7.38
9	67	220-230	3.53	563	1875	3	8	1.10	1.60	15.70	40	2650	750	5.30	0.16	38	105	0.71	3.3
		230-240	3.49	750	2050	2.5	5	0.89	1.05	18.00	30	2200	750	5.00	0.11	38	120	0.93	2.73
	76.2	240-250	3.36	600	1825	2.5	5	1.06	1.30	15.30	30	1950	750	4.90	0.12	38	105	0.99	3.04
10	51.8	170-180	3.68	338	1625	2.5	5	0.69	0.79	18.40	30	1600	950	6.80	0.10	30	135	1.01	4.81
		180-190	3.76	338	1650	2.5	5	0.73	0.47	18.60	30	1600	950	7.20	ND	30	150	1.02	4.88
		190-200	3.73	350	1525	2.5	5	0.73	0.77	16.90	30	1650	750	6.80	ND	30	130	1.33	4.36
		200-210	3.33	488	1675	3	5	0.77	1.05	18.00	30	1750	950	6.80	ND	40	130	0.98	3.43
		210-220	3.63	400	1600	2.5	5	0.84	1.00	18.00	40	2050	850	7.10	0.10	33	135	0.78	4.00
	70.1	220-230	4.19	338	1525	3	5	0.86	0.88	17.10	40	3600	900	7.90	0.11	33	130	0.42	4.51
11	54.9	180-190	ND	538	1825	2.5	5	0.87	0.70	17.10	90	5500	950	9.20	0.14	50	140	0.28	3.39
		190-200	ND	538	1875	3	5	0.96	0.83	17.10	120	9600	980	9.30	0.16	53	145	0.22	3.48
		200-210	ND	650	1875	2.5	5	0.88	0.45	17.10	100	7100	900	9.80	0.16	33	165	0.26	2.88
		210-220	ND	463	1625	3	5	0.79	0.32	18.40	70	5600	750	7.50	0.14	50	140	0.29	3.50
	70.1	220-230	ND	600	1700	3	5	0.85	0.33	18.00	100	6900	800	9.10	0.14	73	155	0.25	2.83
13	64	210-220	4.05	288	1650	5	9	0.66	0.22	18.90	40	2950	1200	10.80	0.14	18	145	0.56	5.73
		220-230	3.87	238	1525	4	8	0.85	0.15	18.00	40	2800	1050	10.10	0.17	20	145	0.66	6.41
		230-240	3.88	263	1650	3	5	0.59	0.10	20.20	40	2600	1050	9.80	0.10	15	145	0.63	6.27
	76.2	240-250	3.90	238	1650	3	5	0.54	0.11	20.00	40	2700	1200	10.40	0.10	18	145	0.61	5.93
15	67	220-230	ND	988	2100	9	13	0.46	0.11	22.60	40	5210	850	7.40	0.04	53	130	0.40	2.12
		230-240	ND	1100	2250	10	13	0.42	0.16	23.80	40	3950	950	7.70	0.06	58	145	0.57	2.04
		240-250	ND	1175	2175	13	18	0.40	0.14	22.40	40	4050	850	7.10	0.04	58	130	0.54	1.85
		250-260	ND	1100	2100	10	15	0.49	0.18	23.20	40	4500	900	7.70	0.06	58	135	0.47	1.91
		260-270	ND	1225	2075	19	23	0.42	0.24	23.20	50	4100	950	7.10	0.04	65	135	0.51	1.69
		270-280	ND	1163	2150	15	23	0.46	0.17	23.00	40	4500	900	7.60	0.04	60	140	0.48	1.85
	88.4	280-290	ND	1125	2150	18	23	0.36	0.27	23.00	40	4050	900	7.30	0.04	60	140	0.53	1.91

Table 23A. Komatiite sample results from 12 rotary drill holes in the Southern Cross greenstone belt. Each sample represents a 3.1 m. interval of ultramafic. The komatiites range from high Mg basalt through to dunite, with a majority of samples in the peridotite range. Most samples, except hole 15, are low in NiP and have Ni/Cr ratios of less than 1 and can thus be classified as Barren. Moderate NiP values are present in hole 15 but Cr results are very high, and in the Barren range.

Hole No.	Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	Ni/Cr	Ni/Nip
14	30.5	100-110	3.12	375	2625	4	8	0.55	0.05	20.40	50	3050	1000	9.30	0.29	43	150	0.86	7.00
		110-120	3.47	225	2250	4	8	0.59	0.05	19.40	40	2550	1050	8.20	0.23	33	140	0.88	10.00
		120-130	3.84	238	2300	125	150	0.59	0.13	18.40	50	3250	950	10.00	0.26	35	150	0.71	9.66
		130-140	3.62	357	2475	53	50	0.55	0.13	19.40	50	3700	1250	10.00	0.26	59	170	0.67	6.93
		140-150	3.15	263	2450	3	5	0.62	0.05	20.40	50	3050	1150	9.30	0.26	50	155	0.80	9.31
		150-160	3.08	325	2500	4	5	0.61	0.03	20.40	50	3600	1000	9.00	0.29	58	155	0.69	7.69
		160-170	3.20	363	2625	3	8	0.62	0.02	19.80	60	3700	950	10.50	0.30	63	165	0.71	7.23
		170-180	3.08	250	2525	3	5	0.59	0.02	20.40	60	3400	1000	9.00	0.29	45	155	0.74	10.10
		180-190	3.16	238	2450	4	8	0.59	0.02	19.80	50	3250	1100	8.80	0.29	53	140	0.75	10.29
	61	190-200	3.54	213	2400	4	8	0.55	0.02	19.80	50	3500	1050	9.00	0.26	40	150	0.69	11.26
12	57.9	190-200	3.98	263	1625	3	8	1.05	0.10	21.00	90	5000	1300	8.80	0.17	28	145	0.32	6.80
		200-210	4.11	275	1575	3	8	1.30	0.29	19.80	80	5000	1100	8.00	0.20	28	135	0.32	5.72
		210-220	4.07	325	1575	20	35	1.05	0.33	19.80	80	4600	1050	8.40	0.19	35	145	0.34	4.85
		220-230	3.89	313	1550	9	13	1.05	0.32	19.80	70	4600	1000	8.00	0.20	35	135	0.34	4.96
		230-240	3.88	463	1500	5	10	0.98	0.68	19.80	80	4750	1150	8.00	0.17	48	140	0.32	3.24
		240-250	4.00	400	1550	3	8	1.15	0.43	20.20	70	4500	1000	8.00	0.23	38	140	0.34	3.87
		250-260	3.92	363	1550	2.5	5	1.05	0.47	20.40	70	4100	1000	8.20	0.20	35	145	0.38	4.27
		260-270	3.98	438	1475	6	18	0.95	0.21	20.40	70	4100	750	8.20	0.20	38	140	0.38	3.37
		270-280	3.65	463	1500	21	30	1.15	0.27	19.80	70	4100	850	8.50	0.20	45	140	0.37	3.24
		280-290	3.66	513	1500	2.5	5	1.15	0.18	20.40	70	4300	800	8.60	0.20	45	145	0.35	2.92
	91.5	290-300	3.76	463	1475	3	8	1.15	0.16	20.40	70	4400	700	8.10	0.17	38	135	0.34	3.19
DDH5	106.7	350	2.60	1125	2175	6	10	1.00	0.24	19.00	90	3950	400	6.90		72	140	0.55	1.93
		360	3.03	950	2200	30	45	0.24	0.05	22.00	60	2250	950	7.20		97	190	0.98	2.32
		370	3.24	975	2025	4	10	0.79	1.50	19.00	80	4500	600	5.80		57	115	0.45	2.08
		380	2.65	725	2025	4	13	0.73	0.43	20.40	80	2700	850	7.00		55	120	0.75	2.79
		390	2.24	1350	2025	4	13	0.91	0.41	19.60	70	1900	950	6.60		95	140	1.07	1.50
		400	2.45	1438	2600	6	13	0.81	0.20	20.40	70	2650	600	5.70		90	155	0.98	1.81
		410	1.91	688	1975	68	90	0.76	0.31	19.00	90	1800	1050	10.80		67	140	1.10	2.87
		420	1.12	688	2125	220	30	0.83	0.36	20.00	70	1800	850	6.90		52	125	1.18	3.09
		430		1250	3625	575	588	1.10	0.03	18.60	80	1900	850	9.80		80	160	1.91	2.90
		440	2.01	663	1750	70	90	1.00	0.19	20.00	90	2000	950	9.80		55	130	0.88	2.64
		450	2.27	1075	2750	58	68	0.96	0.23	20.00	60	2050	700	4.00		67	130	1.34	2.56
		460	1.82	825	2100	14	20	0.94	0.28	21.00	80	2050	650	6.90		65	125	1.02	2.55
		470	2.18	863	2025	38	43	0.77	0.50	20.40	70	2000	750	7.20		70	135	1.01	2.35
		480	1.67	1250	2900	62	80	1.03	0.47	20.00	110	2050	950	6.40		65	145	1.41	2.32
		490	2.48	688	1375	34	38	0.63	0.49	20.40	80	2350	850	7.40		60	115	0.59	2.00
	152.4	500	2.47	975	1900	42	48	0.87	1.08	21.60	70	2150	800	4.80		67	125	0.88	1.95

Table 23B. Additional Southern Cross komatiite results from two rotary holes and a single core hole. The two rotary holes are classified as Barren on the basis of very low Ni/Cr ratios and on their low NiP (S) content. Hole 5 however, has a peridotite section at the base of the hole which has a moderate to low mineralization coefficient, based on canonical scores. This section of komatiite is similar to Marvel Lock A rather than Forrestania, and if sulphides are present they may not be economically significant.

Hole SXP6 (Table 23A) which is south of the Marvel Lock A komatiite that contains nickel sulphides, varies from olivine peridotite to pyroxene peridotite in composition; has Ni/Cr ratios of more than 1 and Ni/Mg ratios of more than 100. NiP content is low (600 ppm) and Ni to NiP ratios average 3.5. Most of the samples from hole 6 fall near the dividing point between Mineralized and Barren and thus could be classified with either group.

Holes SXP7 to SXP10 (Table 23A) contain low to moderate Ni and moderate to high Cr. They can be classified as pyroxene peridotites or peridotit es. They show no evidence of nickel sulphides. Hole SXP11 (Table 23A) contains very high Cr values (average 7000 ppm); hole SXP12 (Table 23B) is peridotitic, with high Cr (4500 ppm) and moderate Ni (1500 ppm); hole SXP14 (Table 23B) is also peridotitic but with high Ni (2500 ppm) and moderate to high Cr (plus 3000 ppm) and Fe. Hole SXP15 (Table 23A) is dunitic in composition with high values of Ni, NiP and Cr. This hole differs from holes 11 to 14 in having relatively low Ni to NiP ratios (1.85 to 2.12), which if the Cr content was lower, could suggest the presence of nickel sulphides.

The results for DDH1 are not shown but were all moderate Ni and high Cr peridotities. DDH's 4 (Table 23B) and 5 both contained a series of samples which were classified Mineralized. These holes intersected peridotite and olivine peridotite with moderate to high Ni and NiP values and moderate Cr values.

6.2.4 Marvel Lock B

At Marvel Lock B (Fig. 52) four diamond drill holes tested a single komatiite complex and all available evidence suggests that this complex is Barren. Geological core logs indicate that the komatiite is overlain at least in part by graphitic-sulphide shale, which contains between 30% and 40% pyrrhotite. The ultramafics are logged mainly as dark green, medium to

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	Ni/Cr	Ni/Nip
79	260	4.17	200	1400	29	38	2.40	1.90	14.60	90	4100	1250	8.60	0.52	23	135	0.34	7.00
	273	3.92	188	1200	24	35	2.25	3.20	14.60	80	3080	1150	9.20	0.49	25	130	0.39	6.38
	280	4.63	88	1050	4	8	2.90	5.20	12.10	80	3050	1300	8.82	0.70	10	120	0.34	11.93
	285	3.86	325	1525	14	18	1.70	2.85	14.60	100	4100	1150	8.50	0.43	33	145	0.37	4.69
	300	3.65	550	1425	49	50	0.83	2.85	17.40	90	4350	1850	9.90	0.16	45	130	0.33	2.59
	310	ND	25	1225	4	10	2.65	5.75	10.20	50	1550	1400	8.00	0.54	5	85	ND	ND
	323	3.09	575	1450	5	10	1.10	1.00	18.10	40	2250	1100	8.40	0.26	35	105	0.64	2.52
	331	1.83	388	2175	2.5	5	1.05	0.56	20.50	60	1000	1100	6.80	0.65	20	120	2.17	5.68
	340	2.26	1000	2150	20	23	0.95	0.63	20.50	40	1600	1250	6.80	0.16	58	130	1.34	2.15
	350	2.62	850	2000	2.5	5	0.81	0.80	20.50	40	1700	1000	6.60	0.10	70	135	1.18	2.35
	358	3.19	88	475	2.5	5	5.00	1.90	9.60	30	500	1150	6.40	0.81	10	75	0.95	5.40
	370	3.26	538	1075	41	55	0.66	1.10	5.80	30	750	400	4.20	0.09	50	95	1.43	2.00
	379	1.87	538	2375	4	8	0.91	0.30	21.20	50	1000	1450	7.30	0.15	35	145	2.38	4.41
	390	4.23	438	2175	20	35	1.01	1.80	16.10	30	3000	550	4.90	0.10	23	110	0.73	4.96
	398	4.65	125	1425	2.5	5	0.49	5.35	17.40	20	1150	1750	2.70	0.07	10	90	1.24	11.40
	412	3.39	888	1850	5	8	0.77	0.76	19.70	50	3850	900	5.90	0.09	58	120	0.48	2.08
	420	4.20	513	2175	2.5	5	0.90	1.20	16.10	50	4700	650	5.70	0.09	33	125	0.46	4.24
	430	ND	488	1075	68	80	0.66	0.08	10.70	60	5200	500	3.00	0.09	38	85	0.21	2.20
	440	3.50	688	1175	3	8	0.45	0.47	5.50	40	2500	550	4.50	0.06	40	55	0.47	1.71
	450	ND	525	2325	3	5	1.15	0.04	18.30	80	1.15%	850	7.30	0.13	23	145	0.20	4.42
	459	ND	363	2300	3	5	1.06	0.02	19.70	50	6600	450	6.00	0.07	15	105	0.35	6.33
	470	ND	363	2075	4	5	0.88	0.03	16.60	60	5200	300	4.60	0.10	20	100	0.40	5.72
	480	ND	463	875	3	5	0.53	1.80	3.05	30	2450	3400	8.30	0.09	43	80	0.36	1.89
	490	3.96	400	1575	4	8	4.70	0.07	18.30	40	3600	2150	4.50	1.29	25	120	0.44	3.94
	500	ND	650	2125	8	13	0.83	0.08	19.70	50	3000	750	5.60	0.16	33	105	0.27	3.27
	510	4.77	275	1950	3	8	0.77	0.81	19.30	30	2100	750	5.00	0.06	28	185	0.93	7.09
	520	3.91	175	2050	3	5	0.79	0.37	19.30	30	2300	600	5.20	0.06	15	115	0.89	11.70
161	528	4.12	500	2100	3	13	0.91	0.50	17.80	50	3050	1050	8.00	0.13	20	145	0.69	4.20

Table 24. Geochemical analyses, canonical scores (B), Ni/Cr and Ni/NiP ratios for an unmineralized sequence of komatiites at Marvel Lock B. Samples are spot core samples selected at irregular intervals over a hole length of 81 m. The ultramafic sequence is heterogeneous and thus volcanic and is high in Cr and low in Ni. A peridotitic section in the center of the hole has a low mineralization coefficient but on the overall results of this hole, and other holes in the area, the sequence has been classified as Barren.

coarse-grained serpentinites with some talcose and amphibolite-rich zones. Chlorite does not seem to be abundant. Traces of sulphide are present.

Sixty spot core samples taken at 3.1 m intervals were obtained from four core holes but only 37 were ultimately used in the statistical analysis (Table 4). The samples rejected were from sulphide shale zones or contained in excess of 5,000 ppm Cr. The results shown in Table 24 (from one hole only) indicate that the komatiite sequence is not homogeneous but contains several individual komatiites which vary in composition from olivine peridotite to high Mg basalt. Cr content is high and ranges up to 1.15%; Ni ranges up to 2375 ppm and Ni$\underline{P}$ varies from low to moderate. Average Ni/Cr and Ni/Ni$\underline{P}$ ratios indicate that the komatiites are Barren. Ni/Mg ratios however, average more than 100. A section of ultramafic approximately 12 m thick has some mineralized characteristics with Ni/Cr ratios of more than 1 and Ni/Ni$\underline{P}$ ratios of between 2 and 3. This komatiite is similar to the possible mineralized komatiite described in DDH5 (Section 6.2.3). Marvel Lock B and C were grouped together for the discriminant analyses - analysis A classified 87% and analysis B 89% of samples as Barren (Table 4).

6.2.5 Marvel Lock C

Marvel Lock C represents a relatively homogeneous komatiite sequence, 8 km northwest of Marvel Lock (Fig. 52). Available geological and drill hole data for this area suggest that it can be classified as Barren. Drill hole logs indicate the komatiites are mottled, green-black, medium-grained serpentinites with widespread fine-grained sulphides, minor talc, carbonate and tremolite. Magnetite and chromite are abundant. Samples were taken at 3.1 m intervals throughout the ultramafic intercepts in two drill holes and the analyses for one hole are shown in Table 25. Total samples collected were 120 but ultimately only 70 were used in the statistical analyses. The results

Depth Meters	Depth Feet	Canonical Score	Nip	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	Ni/Cr	Ni/Nip
73	240	3.44	813	2200	2.5	5	0.85	0.50	19.80	40	4300	550	7.90	0.17	65	125	0.51	2.70
	250	3.24	700	2025	2.5	5	0.85	1.05	20.40	40	3400	450	6.80	0.12	50	110	0.60	2.93
	260	ND	800	2075	4	5	1.20	0.41	19.30	40	6600	500	6.80	0.20	58	115	0.31	2.59
	270	2.57	750	2000	8	10	0.89	1.05	20.10	30	2200	550	5.30	0.15	45	90	0.91	2.67
	280	2.73	1100	2150	4	5	0.64	1.20	19.80	20	2250	500	6.10	0.12	70	100	0.96	1.95
	290	3.46	900	1925	4	5	0.70	2.00	18.40	30	3700	750	5.00	0.08	65	100	0.52	2.14
	300	2.95	838	2125	2.5	5	0.62	1.60	17.30	50	1850	2450	8.20	0.11	108	170	1.15	2.53
	310	3.30	713	2100	3	5	0.85	0.88	21.80	40	2800	1700	5.00	0.11	73	135	0.75	2.95
	320	ND	875	2125	4	5	0.84	0.58	19.80	80	5800	1250	7.10	0.14	63	115	0.37	2.43
	330	ND	1350	2600	4	5	1.00	0.63	19.30	100	7400	1000	5.00	0.17	68	115	0.35	1.93
	340	ND	900	2100	2.5	5	1.10	0.25	19.80	70	6300	850	7.60	0.14	63	115	0.33	2.33
	350	ND	613	2350	2.5	5	0.96	0.04	22.40	100	7500	1350	6.10	0.15	50	130	0.31	3.83
	360	3.47	613	1925	2.5	5	0.64	0.23	22.80	40	3500	950	3.10	0.07	43	90	0.55	3.14
	370	ND	913	2200	2.5	5	1.10	0.04	20.70	60	7500	900	4.50	0.10	53	115	0.29	2.40
	378	3.61	725	2150	2.5	5	0.85	0.49	20.70	40	3750	900	4.50	0.07	33	105	0.57	2.96
	413	4.46	463	2125	2.5	5	0.88	0.09	22.40	20	4100	850	4.00	0.04	25	105	0.52	4.59
	420	4.36	463	2000	2.5	5	1.00	0.04	21.80	20	4200	900	3.80	0.04	28	100	0.48	4.32
	430	ND	650	1925	3	5	1.10	0.68	18.80	90	1.83%	850	4.80	0.08	43	110	0.10	2.96
	440	3.55	763	2225	6	8	0.96	0.33	22.40	80	4700	850	4.80	0.07	60	105	0.46	2.92
	450	ND	863	1925	4	8	1.03	0.51	19.80	60	6650	650	5.70	0.10	58	105	0.30	2.23
	460	3.02	725	2100	5	8	0.92	0.09	23.40	50	3700	950	5.30	0.08	65	125	0.57	2.90
	470	ND	563	1900	6	10	1.10	0.01	22.40	50	5700	900	6.30	0.14	60	130	0.33	3.37
	480	ND	475	1750	4	8	1.10	0.01	20.40	70	5100	800	8.90	0.17	60	130	0.34	3.68
	490	2.82	425	1950	3	5	0.96	0.03	22.40	40	3000	1300	9.70	0.13	53	130	0.65	4.59
	500	ND	738	1900	2.5	5	0.54	0.03	19.80	110	1.07%	850	6.30	0.14	60	140	0.18	2.57
	510	ND	325	1925	4	5	0.83	0.05	23.40	60	5300	1150	5.50	0.14	48	130	0.36	5.92
	520	ND	588	2050	2.5	5	0.91	0.01	22.20	70	5900	800	4.50	0.14	60	115	0.35	3.48
	530	3.62	313	1675	3	5	0.84	0.01	22.80	50	4600	1300	5.00	0.08	53	120	0.36	5.35
	540	3.17	363	1725	2.5	5	0.97	0.02	22.20	60	3950	1250	8.20	0.10	60	130	0.44	4.75
	550	ND	400	1850	2.5	5	0.88	0.03	22.40	60	5200	1050	4.40	0.15	45	120	0.36	4.62
	560	3.37	363	1850	4	5	0.68	0.02	22.80	50	3550	1100	5.00	0.15	50	135	0.52	5.10
	570	3.51	500	1650	3	5	0.89	0.92	20.40	50	4100	1000	8.00	0.14	65	125	0.40	3.30
	600	3.28	725	1500	2.5	5	0.70	1.85	19.30	40	2900	1050	7.10	0.12	73	105	0.52	2.07
	610	3.49	513	1900	4	5	1.00	0.20	22.60	30	3350	600	5.00	0.12	50	120	0.57	3.70
	620	3.70	338	1700	6	8	1.10	2.05	22.20	30	2450	700	5.30	0.16	30	115	0.69	5.02
	630	ND	875	1675	4	13	1.06	0.72	20.40	40	5200	750	5.80	0.12	93	135	0.32	1.91
	640	3.72	363	1750	5	8	0.95	0.39	21.80	30	2300	750	5.70	0.07	30	130	0.76	4.82
	650	3.73	563	1525	2.5	5	1.09	0.29	21.00	30	2900	750	5.70	0.11	55	120	0.53	2.71
	660	3.80	413	1575	3	8	1.02	0.06	21.50	30	2800	650	5.50	0.11	33	115	0.56	3.81
	670	3.84	313	1700	11	15	1.05	0.10	21.40	30	3075	600	5.50	0.11	28	115	0.55	5.43
	680	3.71	263	1550	20	20	1.07	0.09	22.40	30	2500	550	5.70	0.11	28	125	0.62	5.89
	690	2.79	388	1525	6	8	0.92	0.03	22.40	30	1850	650	6.40	0.14	50	120	0.82	3.93
	700	3.38	300	1425	6	8	0.94	0.08	21.80	30	1850	850	5.90	0.14	30	125	0.77	4.75
	710	3.03	250	1500	19	25	1.10	0.06	22.20	30	1450	1150	7.10	0.14	25	120	1.03	6.00
	720	3.82	200	1300	4	5	1.20	0.09	19.80	40	3150	950	6.00	0.05	23	110	0.41	6.50
	730	3.90	275	1000	4	5	1.10	2.10	18.60	50	2850	1550	5.30	0.14	35	105	0.35	3.63
	740	6.17	25	400	3	5	1.20	4.55	13.80	30	2450	950	4.50	0.21	5	70	0.16	16.70
	750	5.84	25	450	3	5	1.60	?2.85	14.50	30	2000	800	4.80	0.63	5	80	0.23	18.00
	760	5.86	25	475	2.5	5	1.20	1.50	15.30	40	2500	900	5.50	0.29	5	80	0.19	19.00
	770	6.30	25	375	2.5	5	1.50	2.40	14.20	50	2650	1350	6.30	0.24	5	95	ND	ND
	780	6.21	25	375	95	98	2.00	1.70	13.80	60	2650	1500	7.20	0.34	5	105	ND	ND
	790	5.87	25	350	4	8	1.35	1.30	14.20	70	2400	1550	7.40	0.28	5	100	ND	ND
	800	5.85	25	325	4	8	1.70	1.40	13.20	70	2300	1550	7.90	0.32	5	100	ND	ND
247	810	5.89	25	325	3	8	1.70	1.85	13.20	70	2250	1500	7.60	0.33	5	95	ND	ND

Table 25. Marvel Lock C represents a thick, probably intrusive peridotitic komatiite or komatiites, with extremely high Cr and very low Cu contents. It can be classified as Barren with confidence.

are similar to Marvel Lock B except that low Cu, Peridotitic to dunitic komatiites, dominate. The distinguishing feature is the very high Cr content with individual results of up to 1.83% Cr.

The NiP values range from low to moderate but apparently do not reflect the widespread disseminated sulphide present in the ultramafic. Some Ni/NiP ratios and Ni/Mg ratios which average more than 100 are indicative of mineralized komatiites. However, the widespread very low Ni/Cr ratios and the fact that Ni/NiP ratios are erratic support a Barren classification.

6.2.6 Ennuin

The Ennuin area is situated within the northern section of the Southern Cross greenstone belt approximately 56 km north of Southern Cross (Fig. 28). Nine core holes totalling approximately 1500 m were drilled in two parallel volcanic komatiite suites along a strike length of 6 km. The rock types present include coarse to fine-grained amphibolities, banded iron formation and ultramafic rock. The sequence at the western komatiite from east to west is: coarse-grained amphibolites, possible metagabbro, komatiite sequence, which varies from 50 to 500 m in width; banded iron formation; fine-grained amphibolites; coarse-grained amphibolites, chlorite schists and metabasalts. The komatiites were mapped as serpentinites and talcose ultramafics.

Samples were obtained from six core drill holes (spot core 3.1 or 6.2 m intervals) from within the western komatiite sequence and two within the eastern komatiite sequence. Total samples analyzed numbered 145 but some of these were not ultramafic and 129 samples were used in the statistical analysis. Discriminant analysis A classified 83% and analysis B 90% (Table 4) of samples as Barren. The sequence is low in NiP, Ni and Mg and relatively high in Cr and Fe.

Hole No.	Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co
A	70	200	3.69	300	1525	6	13	1.30	0.44	16.90	50	2550	850	8.00	0.17	35	135
		210	ND	25	325	5	20	7.20	8.40	6.00	50	1050	1250	6.90	0.42	5	75
		220	4.84	25	450	2.5	8	4.00	4.40	12.40	50	700	1100	8.00	0.48	5	110
		230	3.59	438	1425	38	40	1.30	0.32	15.30	40	2450	700	7.40	0.15	48	135
		240	4.93	25	325	2.5	5	5.70	4.40	10.60	100	1600	2150	11.40	0.83	5	105
		275	5.23	25	925	2.5	5	2.00	1.70	13.20	40	2050	650	9.50	0.31	5	110
		280	3.60	463	1500	10	15	0.95	2.25	14.50	40	3000	1350	10.50	0.13	33	105
		290	3.32	263	1500	6	10	1.30	0.35	15.00	40	2250	350	9.30	0.18	33	120
		300	3.89	25	1225	2.5	5	0.95	0.02	15.00	40	1500	200	7.40	0.09	5	95
		310	3.93	225	1475	16	20	1.90	3.10	14.50	40	3050	900	8.20	0.26	25	105
		330	4.80	50	1325	2.5	5	1.90	3.60	14.10	50	3150	1100	8.20	0.23	10	105
		340	3.65	188	1575	3	8	1.05	0.68	14.10	50	3100	450	11.10	0.10	25	105
		348	5.04	25	1325	2.5	5	1.15	0.21	13.40	50	3650	250	13.30	0.14	5	115
		410	4.20	188	1375	5	10	1.40	4.60	13.60	50	2800	800	5.80	0.19	25	105
		420	3.98	150	1375	4	8	1.40	1.80	15.40	40	2200	1250	5.40	0.14	20	100
		430	3.84	138	1700	8	8	1.40	1.10	16.90	40	3000	1000	6.20	0.18	25	110
		440	4.72	38	1550	18	23	1.05	1.05	16.90	40	2500	1150	6.20	0.14	8	105
		450	4.41	100	1800	3	5	1.40	0.81	16.90	40	3100	750	5.10	0.15	15	115
		460	4.88	38	1725	10	13	1.30	1.10	16.40	30	2900	600	5.80	0.17	13	110
		470	4.46	138	1825	2.5	5	1.30	1.25	16.90	30	3050	550	5.10	0.17	25	110
		480	4.01	125	1725	5	8	1.15	1.05	16.90	40	2700	950	6.40	0.22	25	115
		490	4.41	125	1800	3	5	1.15	0.26	16.90	30	3500	650	5.80	0.14	20	110
		500	4.45	138	1625	319	300	1.05	0.87	16.40	30	2650	1050	7.40	0.14	28	115
		510	3.73	300	1775	4	8	1.15	0.19	17.40	30	2750	1000	6.10	0.14	35	120
		520	3.67	550	1775	5	8	1.15	0.71	16.90	30	2550	1150	5.60	0.14	35	115
		525	3.96	500	1225	30	43	1.15	5.75	13.20	40	2050	1200	6.40	0.14	38	115
	161	528	ND	175	225	173	183	6.60	3.30	3.10	220	300	1350	11.10	1.04	53	90
B	67	220	4.45	50	625	3	8	5.60	4.30	8.40	100	1900	1050	9.30	0.94	13	115
		230	2.95	750	1500	119	130	2.35	5.20	12.40	80	2050	1250	8.20	0.71	43	130
		240	2.69	850	1600	96	98	2.00	4.60	13.50	90	2250	1300	9.00	0.88	48	125
		250	2.77	825	1500	48	50	2.10	5.30	13.50	80	2350	1350	9.50	0.77	50	125
		260	2.53	1025	1675	118	113	2.70	3.70	14.10	80	2100	1550	9.60	0.89	65	145
		270	3.65	188	1275	55	58	2.90	4.85	13.00	90	2600	1650	10.50	0.97	25	135
		280	2.61	200	1325	4	8	3.90	2.25	15.90	80	1400	1050	7.00	0.45	23	120
		290	2.95	463	1300	44	50	2.20	5.20	12.80	80	2250	1250	9.20	0.83	40	115
		300	2.67	488	1275	16	20	2.20	4.25	14.10	70	1750	1300	7.70	0.66	33	110
		310	3.67	538	825	18	98	2.70	5.30	11.00	100	1850	1550	9.00	0.90	35	110
		320	ND	50	1275	ND	33	1.50	5.45	13.20	70	2150	1350	7.70	0.65	10	105
		330	2.90	438	1450	26	23	2.10	4.60	13.20	80	2250	1350	7.70	0.77	33	120
		340	2.60	613	1675	58	65	2.90	3.70	14.50	90	2150	1450	8.80	0.65	38	125
		350	2.79	563	1500	39	50	1.90	4.00	14.50	80	2000	1400	8.50	0.62	40	125
		360	2.61	550	1325	101	103	1.60	5.00	13.20	80	1600	1300	7.40	0.51	38	110
		370	3.31	363	1200	84	90	1.60	5.45	12.80	70	2150	1300	8.50	0.66	28	105
		380	3.08	625	1375	153	158	1.90	4.85	12.80	80	2450	1350	9.30	0.77	48	120
		390	2.43	925	1950	9	13	1.75	2.70	15.90	90	2450	1350	9.00	0.68	53	135
		400	2.78	538	1450	45	50	1.90	4.25	13.60	90	2250	1250	8.80	0.74	38	120
		410	3.12	538	1325	43	45	2.10	4.70	12.80	80	2650	1250	9.90	0.83	45	125
		420	2.87	525	1425	59	65	1.90	5.20	13.60	70	2050	1250	9.50	0.58	35	115
		430	5.33	25	750	56	65	3.05	4.70	10.60	100	2750	1450	11.10	1.11	5	125
		440	2.35	625	1925	26	33	1.50	2.55	17.00	90	1800	1450	8.80	0.56	33	140
		450	2.43	700	1725	41	48	1.75	3.40	16.40	90	1950	1350	8.20	0.59	28	130
		460	3.09	663	1400	66	68	1.50	5.90	12.40	80	2550	1400	10.50	0.74	45	125
		470	2.57	713	1450	26	50	1.40	5.90	12.40	170	2750	1350	10.50	0.64	48	120
		480	3.26	638	1375	113	122	1.75	5.45	12.80	90	2450	1350	9.00	0.64	48	130
		490	3.84	313	1100	14	20	1.50	5.80	12.80	70	2750	1250	8.80	0.70	28	115
		500	3.04	500	1700	8	13	2.35	2.40	16.40	100	2850	1650	9.30	0.68	35	150
		510	3.38	475	1300	96	103	1.15	6.20	12.80	70	2300	1150	8.00	0.54	28	105
		520	3.27	513	1425	19	23	1.90	4.25	14.50	70	2550	1400	8.00	0.58	35	125
		530	ND	688	1475	920	975	2.10	5.20	13.20	70	2050	1150	9.60	0.57	50	125
		540	1.97	1025	1800	313	333	2.90	3.40	14.50	180	3000	1100	10.20	0.77	65	125
		550	2.97	525	1625	13	18	2.35	2.70	15.90	90	2900	1550	9.30	0.65	40	140
		560	4.57	38	1000	4	8	3.05	4.10	12.80	90	2750	1300	10.50	0.95	10	125
		570	2.77	863	1900	78	88	1.40	3.85	15.00	70	2250	1100	7.70	0.40	45	125
		580	2.93	650	1700	19	23	1.75	3.30	15.00	70	2350	1350	9.00	0.51	38	130
		590	3.85	375	1175	68	73	1.60	6.00	12.40	70	2900	1300	8.20	0.65	30	115
		600	2.79	563	1625	15	18	2.00	4.10	14.50	90	2600	1450	8.50	0.65	38	125
		610	3.04	925	1650	44	48	2.35	4.40	14.10	70	2800	1250	8.60	0.58	48	130
		620	2.63	700	1575	40	43	1.75	4.00	14.50	90	2250	1250	8.20	0.54	43	125
		630	3.18	325	1075	53	53	2.10	4.85	12.80	90	2650	1250	9.60	0.58	33	105
		640	3.06	825	1475	103	108	0.90	6.35	11.90	70	2300	1250	7.40	0.54	48	105
		650	2.77	263	1275	104	100	3.05	3.40	14.50	100	1600	1500	8.80	0.54	30	135
		660	3.57	188	1050	23	28	2.60	4.40	13.20	100	2550	1350	8.50	0.54	20	115
		670	3.16	388	1175	16	18	2.00	5.00	12.80	90	2850	1550	10.50	0.86	35	115
		680	2.59	900	1700	24	28	1.90	3.10	15.00	100	3150	1250	8.50	0.54	60	125
		690	2.31	383	2100	5	8	2.00	1.55	13.00	110	2100	1450	9.60	0.57	25	145
		700	2.89	763	1575	64	70	1.60	4.40	14.50	90	2500	1400	9.30	0.66	48	135
		710	2.71	850	1700	46	50	1.75	3.40	14.50	90	2550	1400	9.60	0.66	55	140
		720	1.52	1150	2550	14	18	2.00	0.33	19.80	120	2250	1550	9.90	0.44	68	170
		730	1.49	750	2225	3	5	1.15	1.40	18.40	90	1650	1400	8.80	0.25	48	125
		740	3.11	1300	2100	138	138	1.60	3.70	14.10	110	4650	1350	11.70	0.82	70	155
		750	1.98	1763	2700	24	25	1.75	3.00	15.90	100	2900	1350	7.40	0.57	78	145
		760	1.93	625	1525	26	28	1.60	3.85	15.90	70	1300	1250	7.00	0.26	28	100
		770	1.79	813	1450	110	110	1.75	4.85	13.60	210	2050	1250	7.70	0.54	58	120
		780	4.60	63	775	2.5	5	2.60	4.10	12.80	80	2550	1200	11.40	1.05	3	115
		790	2.51	950	1600	64	68	2.00	4.70	13.60	90	2350	1050	8.20	0.88	65	125
	243	797	4.30	50	775	3	8	3.05	5.60	10.20	100	2250	1350	9.30	0.89	13	105

Table 26. Geochemical analyses and canonical scores for komatiite samples from two core holes at Ennuin. Ennuin is a Barren, volcanic sequence as is illustrated by the variability in the geochemical analyses and the relatively low Ni and high Cr results. Some samples near the base of hole B have low mineralization coefficients caused by higher Ni and slightly low Cr values. They are not regarded as significant.

Hole A (Table 26) represents the western komatiite sequence. This sequence is low in Ni, has very high Ni to NiP ratios, and is high in Cr compared to the eastern komatiite sequence (Table 26). Mg and Ni results tend to increase with depth and it is suggested that these komatiites are a sequence of differentiated thick units (each 20 to 30 m thick) from a volcanic suite. Hole B, in contrast, is much more variable in magnesium content, contains higher copper values and represents a series of thin volcanic units such as the thin units at Kambalda. NiP values vary from low to quite high with resulting Ni/NiP ratios as low as 1.5. However, corresponding Ni/Cr ratios are almost invariably less than 1 which together with the generally low total Ni results suggest that the komatiites in this area are unlikely to host nickel sulphide deposits.

6.2.7 Bullfinch

Bullfinch represents two intrusive suite komatiite sequences near the northern end of the Southern Cross greenstyone belt (Fig. 28). It has already been described in some detail in Section 4.2.3.

Bullfinch komatiites are regarded as Barren. they have high Mg (24%), Ni (2110 ppm), moderate Cr (1581 ppm) and low Cu (9 ppm). The Ni/Mg ratio is similar to Forrestania komatiites but Cr values are higher and NiP values lower than Forrestania. Ni/NiP ratios are in the range 3-7 and can be regarded as indicative of a Barren classification.

6.3 DISCUSSION

Chemically the Southern Cross-Forrestania komatiites form a separate series (Fig. 5) distinct from komatiites in all other areas sampled in this study. The Southern Cross komatiites differ from Forrestania komatiites as follows:

1. Forrestania komatiites contain low Cr and Fe whereas Southern Cross komatiites are high in Cr and Fe with Cr values of up to 2%.
2. Southern Cross komatiites are predominantly pyroxene peridotites with subordinate peridotites and dunites whereas Forrestania komatiites are predominantly peridotites and dunites.
3. Many of the Southern Cross high Mg komatiites are relatively low in Ni with Ni/Mg ratios as low as 50. The Forrestania komatiites are uniformly high in nickel.
4. The Forrestania komatiites have distinctive and fairly constant geochemistry over a strike length of 30 to 60 km and widths of up to several hundred meters. Southern Cross komatiites have variable geochemistry.

Marvel Lock A represents a Mineralized intrusive suite within the Southern Cross section of the belt. However, the Marvel Lock A komatiites appear to have a geochemical signature distinct from the Forrestania komatiites. Marvel Lock A komatiites differ from Forrestania in having higher Cu, Fe, Cr and Co contents. Marvel Lock A however, is still regarded as an example of a mineralized komatiite sequence. Other intrusive suites such as those intersected in holes SXP1, 3, 12 and 13, although olivine peridotite in composition, are relatively low in Ni content. Holes such as SXP15 which have high Ni and Ni/Mg ratios of about 100 also have very high Cr contents.

Marvel Lock B and C komatiites both contain fine-grained disseminated sulphides. However, Ni/P values are low to moderate which suggests that the sulphur has been added to the komatiites after crystallisation by metasomatic transfer from adjacent sediments from the komatiites.

There are possible Mineralized komatiites in DDH5 and at Marvel Lock B within an overall unmineralized sequence. The komatiites immediately adjacent to the possible mineralized komatiites have high to very high Cr and low Ni/P. Consequently it is considered unlikely that these isolated komatiites which are apparently Mineralized have any great significance.

To sum up, the chemistry of the Southern Cross komatiites indicates that a nickel province of the size or potential importance of the Forrestania Nickel Province does not exist in the central and northern parts of the Forrestania-Southern Cross greenstone belt. It may also indicate that the stratigraphic section at Forrestania is not stratigraphically equivalent with Southern Cross sequence further north - being either younger or older. However, the known mineralization at Marvel Lock A and Trough Wells, plus the komatiites classified as Mineralized by Discriminant Analysis B in DDH's 4 and 5 suggest that minor nickel sulphide mineralization may be present in very scattered areas of the Southern Cross greenstone belt.

CHAPTER 7

7.

APPLICATION OF GEOCHEMICAL CRITERIA TO NEW AREAS AND SAMPLE GROUPS WITH HIGH DEGREE OF MISCLASSIFICATION

In this chapter the geochemical criteria outlined in earlier chapters will be applied to several unknown areas. Sample graphs which appear to be misclassified by the discriminant analysis will also be discussed.

7.1 APPLICATION OF GEOCHEMICAL CRITERIA TO NEW AREAS

Two areas of unknown affinities were evaluated using the discriminant function and geochemical criteria developed in this study. They are designated Area B and C. Area C komatiites are geochemically similar to Forrestania, have a high Mineralization coefficient and could contain large deposits of nickel sulphide.

7.1.1 Area B

Area B is situated in the southern part of the Kalgoorlie-Norseman Nickel Province. The geology of Area B greenstone belt is shown in Fig. 53. The rocks consist of steeply dipping, probably tightly folded metamorphic rocks. Original rock types were dunite, peridotite, pyroxenite, gabbro, basalts and various sedimentary and volcanic derived rocks. At the southern end the rock sequence is terminated by granite. The regional dip is to the west but facing evidence (ultramafic flow tops) suggests that the sequence faces east.

As in most greenstone belts, the rocks can be divided into four broad categories: komatiitic ultramafics, mafic, meatsedimentary and granitic. The komatiites consist of the following mineral assemblages: serpentine, talc-carbonate, tremolite-talc-carbonate, talc-tremolite and tremolite-chlorite. They can be divided into three sequences - designated western, central and eastern ultramafics. The western ultramafic in the northern part of the area has a strike length in excess of 20 km, averages 300 m in thickness and ranges up to 600 m. It consists at surface of a dark grey, fine-grained serpentinite with minor tremolite and chlorite and may represent at least in part, an intrusive peridotite or dunite. The ultramafic

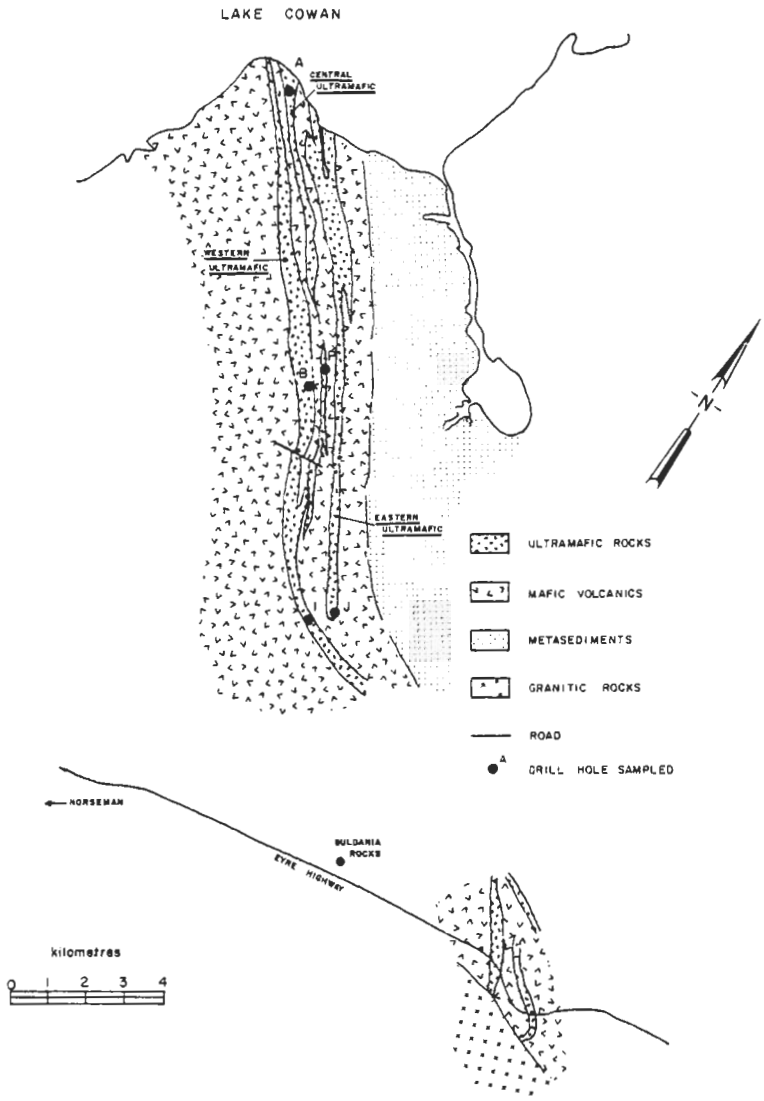

Fig.53 . Interpretive geology of the Buldania area showing disposition of main ultramafic sequences and the location of some holes sampled.

is strongly magnetic and the fresh serpentinite contains up to 18% magnetite. The central ultramafic is much smaller than the western ultramafic and extends intermittently along a strike length of 12 km. It averages 150 m thick and ranges up to 600 m near the shores of the lake, where at least three individual ultramafic units can be distinguished. The eastern ultramafic includes a variety of rock types and in the northern area it can be traced over a strike length of 15 km. It is at least 600 m thick near the lake but thins significantly to the south. This ultramafic sequence is mainly of extrusive origin (thin units). Most surface exposures are of serpentine or talc carbonate rocks but tremolite and tremolite chlorite rocks are much more common than in either the central or western ultramafics. At the lake individual flows 1 m to 8 m in width outcrop and textures such as spinifex zones and flow top breccias are well developed. Interflow shales and cherts also occur.

The mafic rocks are composed of tholeiitic metabasalts, metagabbro and amphibolites of uncertain origin. Gemuts and Theron (1975) indicated significant thicknesses of mafic rocks in this area as intrusive mafic complexes, but this was not substantiated in the present work.

Thin metasedimentary units, bedded cherts and graphitic black shales occur throughout the greenstone belt but appear to be more common east of the western ultramafic. In the southern area, one sediment horizon is 150 m in thickness, but average thickness for these units is 10 m. Sulphide (pyrite and pyrrhotite) content detected in rotary drill holes is as high as 15%. Several areas in or near u ltramafic rock apparently have concentrations of lead and zinc up to 10%. The origin or significance of these occurrences is still speculative.

A total of 87 samples from sixteen rotary holes were sampled but the distribution of samples is uneven with most samples originating from the small southern area. In addition, some holes were relatively shallow and oxidation effects may have penetrated the samples collected. Discriminant analysis B classified 42% of the samples as Mineralized and 58% as Barren. A frequency distribution plot (Fig. 54) shows that the canonical scores are polymodal and at least two and perhaps more populations are represented in the samples. The plot for Kambalda is similar. Canonical scores for most samples and all geochemical analyses are listed in Table 27. Samples from holes A, E, G, K and M all show moderate to high mineralization coefficients; holes D and N contain many borderline samples and the remaining holes are barren. The komatiites are mainly low nickel and magnesium varieties, indicating that the samples mainly represent thin units. Sulphur content, as indicated by NiP analyses are mainly moderate to low with a few high results. Some samples from holes A, D, E, G, K and O based on Mg content can be classified as peridotites while the remaining samples are mainly pyroxene peridotites. Hole A, which is at the northern end of the central ultramafic, contains three samples with a high mineralization coefficient. Further investigation of this komatiite is warranted.

The cluster of holes with moderate to high mineralization coefficients in the southern part of the area (Fig. 55) are also of interest and indicate that some komatiite units in that particular sequence could contain sulphide deposits.

The holes sampled are too widely scattered to provide positive conclusions as to the potential of the entire area but there is sufficient encouragement to suggest that some of the komatiite present could host nickel sulphide deposits.

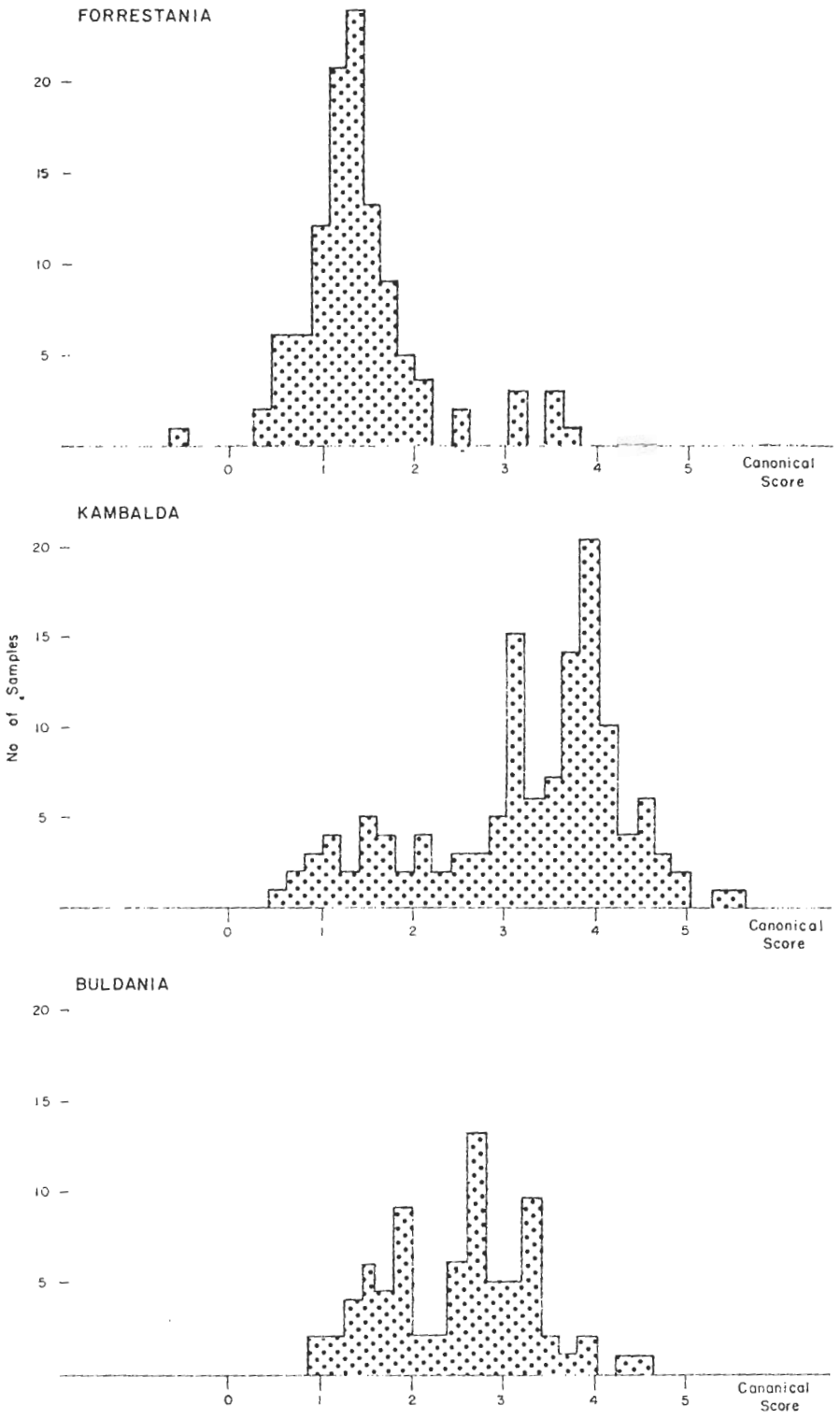

Fig. 54 . Frequency distribution plots of canonical scores (Discriminant Analysis B) for Forrestania, Kambalda and . Note the single population or homogeneous nature of Forrestania and the multiple populations and heterogeneous nature of Kambalda and Buldania.

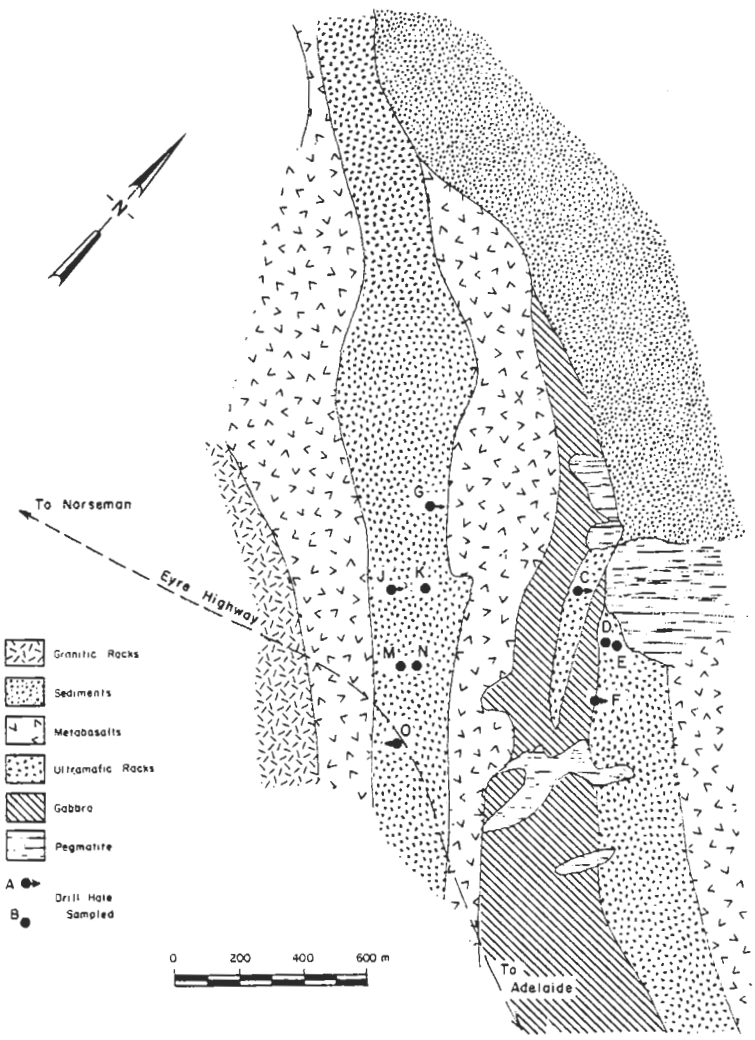

Fig. 55. Interpretive geology of southern part of the Buldania area showing location of holes sampled.

Hole No.	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co
A	1.10	800	1525	12	25	2.30	2.25	17.40	90	1200	950	6.70	48	90
	1.48	763	1425	24	40	2.40	2.55	16.90	90	1250	950	6.20	48	90
	1.22	750	1450	24	43	2.60	2.55	16.90	90	1100	1000	6.20	45	90
	ND	125	1200	6	13	3.70	5.85	13.70	390	1500	1100	6.90	15	100
	ND	50	750	100	105	4.30	4.85	13.70	1380	1300	1200	7.20	8	100
	3.36	88	1550	8	90	1.40	3.15	16.30	120	1100	1300	7.70	5	95
B	3.21	100	1550	8	93	1.55	2.95	15.80	120	1000	1300	7.90	5	100
	3.17	100	1500	8	80	1.40	3.30	15.80	120	1000	1300	7.90	5	95
	ND	75	700	114	130	5.40	5.00	11.00	3800	1400	1450	8.35	15	110
	1.81	325	1500	48	58	1.70	4.40	14.60	100	1150	1350	7.30	30	100
	2.42	263	1350	58	75	1.70	5.15	13.20	80	1150	1400	7.90	28	105
	1.88	263	1400	78	93	1.70	4.55	13.70	90	900	1400	7.60	25	95
	1.99	350	1550	176	200	1.80	4.00	14.60	90	1100	1400	8.60	35	105
	2.65	200	1150	140	155	2.10	5.15	13.70	80	1300	1600	8.90	25	100
	2.58	388	1350	76	95	2.00	4.40	15.20	100	1900	1400	7.90	40	110
C	3.23	475	950	40	50	2.40	3.15	15.80	90	2300	1200	7.30	70	130
	3.31	450	900	46	60	2.40	3.60	15.20	90	2200	1300	8.10	65	135
	3.02	500	900	60	73	2.60	3.45	15.20	100	2150	1350	8.10	70	130
	3.30	450	875	64	78	2.40	4.00	14.20	80	2100	1150	7.90	65	125
	3.19	413	750	72	100	2.70	4.15	12.80	110	1850	1300	8.10	60	125
	3.34	313	750	52	85	2.50	3.45	12.80	120	2000	1300	8.35	40	125
	2.70	463	750	60	73	2.60	4.20	14.20	100	1500	1500	8.10	55	120
	3.41	300	650	64	88	2.40	4.30	14.40	90	1700	1700	8.50	45	110
D	2.68	575	1350	25	45	2.40	2.75	16.60	110	2950	1100	8.10	55	110
	ND	550	1450	1033	1120	1.60	4.10	15.30	120	1550	1300	8.30	50	110
	2.47	700	1325	30	38	2.60	2.25	17.50	100	2050	1150	8.10	65	110
	2.71	563	1300	44	55	2.30	2.35	17.40	100	3000	1200	8.10	53	115
	2.74	738	1350	40	48	2.60	3.15	17.60	100	3250	1300	7.90	65	120
	2.64	600	1250	50	60	3.30	3.45	16.00	100	2500	1250	7.60	55	115
	2.43	688	1350	36	45	2.70	2.35	15.60	120	2900	1200	7.80	55	115
	2.39	675	1250	48	53	2.40	4.00	15.00	150	2900	1350	7.40	50	110
	2.84	713	1350	12	20	2.30	2.60	17.10	90	3100	1100	7.90	55	120
E	1.42	875	1650	8	10	2.30	3.35	17.10	100	1850	900	6.70	55	100
	1.41	888	1600	8	10	2.40	3.15	16.60	100	1800	900	6.70	55	100
	1.19	900	1350	72	90	2.95	3.80	14.20	210	1800	1050	8.30	50	95
F	3.05	88	900	20	28	3.70	5.45	12.40	180	2200	1200	8.10	10	90
	2.78	250	950	44	50	3.40	4.70	12.80	150	2300	1250	8.10	25	100
	3.32	150	950	24	53	3.15	4.85	12.80	140	2300	1200	7.90	20	95
	2.74	375	1050	70	90	3.00	4.85	13.70	120	2200	1300	7.90	35	105
G	1.30	800	1900	24	40	1.30	2.35	15.80	90	1100	1050	9.50	55	110
	1.99	800	1950	16	30	1.15	1.70	16.60	60	1100	1000	8.10	55	105
	1.89	838	1850	30	85	0.91	1.70	14.60	60	1200	1150	7.90	60	100
	1.07	925	1350	144	175	1.30	5.10	13.30	250	1350	1350	8.80	53	100
	2.75	350	1050	52	65	1.60	5.70	13.30	70	1500	1600	9.00	38	95
	1.63	963	1700	8	13	1.00	2.70	18.10	50	1050	1350	6.90	68	110
	0.99	1400	2150	4	10	0.32	1.25	19.10	60	1000	1100	7.20	90	110
	1.37	1325	2000	8	20	0.91	2.55	17.60	50	1000	1100	6.90	95	115
	1.46	1088	1750	12	20	0.35	3.80	16.00	90	1200	1300	7.80	85	115
	1.71	925	1550	208	207	1.30	5.15	14.60	80	1300	1450	8.10	75	105
H	2.57	150	1250	100	133	1.30	5.60	13.10	90	1250	1300	8.10	43	100
	2.81	150	1000	96	105	2.00	5.45	12.80	90	1100	1500	7.90	35	110
	2.73	125	1050	46	93	1.85	5.30	12.40	90	1000	1500	7.60	30	100
	2.53	313	1025	112	135	2.10	5.15	12.60	110	1350	1500	7.90	33	110
	3.37	128	725	50	100	2.85	6.30	11.00	100	1300	1500	9.30	20	100
I	3.97	83	1450	8	50	2.60	3.85	13.70	100	1900	1200	8.20	10	95
	4.30	38	1250	6	53	1.60	3.80	13.30	100	2300	950	7.50	5	105
	4.36	50	1300	2	40	1.10	4.30	13.30	110	2100	850	8.30	8	100
	4.58	83	1350	4	40	1.15	4.00	12.40	80	2200	900	8.70	5	100
	ND	83	1500	ND	25	2.85	5.15	12.80	90	1900	900	8.00	8	100
	3.94	113	1950	2	25	3.00	5.45	12.80	80	2200	850	7.20	13	95
J	2.61	250	350	116	125	2.30	3.40	11.50	130	1650	1700	10.20	30	100
K	1.54	575	1300	48	55	1.40	5.45	13.70	100	1450	1550	9.50	53	110
	1.90	600	1500	44	55	1.40	5.60	14.60	90	1250	1400	8.80	38	110
	1.57	675	1950	8	15	1.00	3.20	18.10	80	950	1200	7.60	18	110
	ND	438	2050	ND	10	0.55	2.70	18.10	70	850	1100	7.60	10	100
	ND	500	2050	ND	10	0.85	2.20	19.40	70	900	1100	7.00	10	100
	0.93	813	2100	24	35	0.81	1.50	19.40	80	800	900	7.90	18	100
L	ND	450	1250	52	78	2.30	11.70	8.30	170	1100	1900	8.50	35	105
	ND	375	1125	48	65	2.50	11.30	9.20	160	1100	2400	9.80	35	100
M	1.78	488	1600	44	60	1.30	4.30	16.00	70	1150	1200	8.80	50	110
	1.75	725	1500	12	25	2.00	4.70	14.60	50	1100	1250	8.50	55	105
	1.86	850	1400	124	125	2.00	5.15	14.20	80	1200	1400	8.60	60	110
	1.85	475	1150	60	65	2.30	6.30	12.30	110	1300	1550	9.00	50	105
N	1.39	475	1550	8	20	1.30	4.30	15.60	100	1200	1400	8.30	30	110
	2.78	563	1550	2	15	1.40	4.70	15.00	70	1200	1500	8.60	23	110
	2.86	488	1525	2	13	1.40	5.45	14.60	80	1300	1350	8.80	15	110
	2.51	450	1300	18	35	2.30	5.35	13.70	90	1400	1700	9.30	25	110
	2.03	550	1550	24	40	1.60	4.35	15.30	90	1350	1100	8.70	30	110
	1.54	738	1675	20	30	1.60	3.85	16.30	90	1200	1150	8.50	45	110
O	2.33	513	1600	18	35	1.10	4.85	15.60	90	1250	1400	8.50	20	115
	3.10	450	1600	14	35	1.10	5.30	17.10	80	1200	1350	9.50	20	160
	2.83	300	1600	52	93	1.30	4.70	16.30	80	1300	1400	8.50	15	120
	1.73	163	1075	72	145	2.00	7.45	13.30	70	1400	1900	9.30	13	110
P	2.36	1750	3075	54	58	5.40	4.55	5.60	100	2350	1200	7.30	70	170
	3.50	775	1950	50	70	5.40	4.55	5.20	100	2700	1250	6.70	45	140
	2.14	1213	2075	52	78	4.30	3.65	9.20	180	2750	1250	8.30	30	140
	3.37	913	2150	56	75	5.70	5.15	5.00	140	3100	1300	7.20	50	185

Table 27. Geochemical analyses and canonical scores (B) for komatiite samples from 16 rotary drill holes at Buldania

The sequence as sampled is predominantly thin units, but some peridotitic, probable thick units, with moderate Ni and low Cr are present. Note that most holes are consistent in that all samples in each hole are predominantly Mineralized or Barren. In particular holes G and K show moderate to high mineralization coefficients.

7.1.2 Area C

Area C is approximately 150 km north-northeast of Kalgoorlie and is part of a thick northwesterly trending mafic-ultramafic sequence. Rock outcrop is sparse and consists of metadolerite, metagabbro and serpentinite with interbedded or interlayered metasediments and minor acid porphyry and aplite. Some 20 deep rotary holes and two diamond core holes were drilled and minor trace sulphides were encountered throughout the ultramafic. Nineteen spot core samples were obtained from one diamond drill hole over a core length of 150 m. Sample interval is irregular, but approximates 15 m.

Thin sections showed the ultramafic is a partially serpentinized dunite containing exsolved magnetite and traces of sulphides. Relict granules of olivine are enclosed in a reticulate mesh of serpentine (which is the predominant mineral). The dunite was apparently medium-grained and contained little interstitial material. The magnetite is present in grains up to 1 mm in diameter, but is generally fine-grained and disseminated. Several samples were found to contain rare, very fine-grained specks of pentlandite. The petrographic examination suggests that at least this section of the ultramafic sequence is a homogeneous, dunitic komatiite belonging to the intrusive suite.

Canonical scores for analysis B were calculated manually (Table 28). 94% of samples were classified as Mineralized and the majority of samples have a high to very high mineralization coefficient. Chemically, the komatiites contain high Ni and Mg; moderate Ni/P and low to very low Cr, Mn, Fe and TiO_2. These results are similar to Forrestania and Queen Victoria Rocks, and although the sample size is small, indicate that the Area C komatiites represent a mineralized intrusive sequence. Nickel sulphide accumulations are likely to be associated with these komatiites.

Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	S	Ni/Cr	Ni/NiP
1.53	1015	2900	4	7	0.65	0.50	24.20	40	800	650	4.80	0.05	35	140	0.065	3.62	2.86
0.86	1015	2800	2	4	0.70	0.54	23.95	40	750	700	5.20	0.06	27	120	0.04	3,73	2.75
3.20	265	1200	4	35	0.25	13.30	17.55	40	500	1200	3.20	0.03	15	120	0.015	2.40	4.53
1.31	1150	3050	4	7	0.35	0.20	23.40	50	950	400	5.20	0.03	47	140	0.07	3,21	2.65
1.13	875	2650	4	6	0.31	0.28	24.70	50	800	650	6.00	0.04	55	140	0.185	3.31	3.03
1.01	1050	2825	4	6	0.65	0.02	23.95	40	850	350	5.65	0.05	37	140	0.105	2.69	2.69
1.57	1100	2700	18	21	0.21	1.88	24.40	40	800	900	4.80	0.13	45	120	0.07	3,37	2.45
1.20	1050	2900	4	7	0.64	0.60	25.10	50	800	750	4.60	0.06	50	140	0.115	3.62	2.76
1.64	775	2750	2	7	0.77	0.96	24.40	50	750	1000	5.20	0.06	35	140	0.05	3,67	3.54
0.93	975	2500	14	17	0.81	0.20	24.90	50	750	650	4.15	0.09	47	120	0.095	3,33	2.56
0.47	875	3000	8	11	0.88	0.84	23.95	70	900	950	5.65	0.09	32	140	0.08	3,33	3,43
1.92	165	2625	14	20	1.10	2.02	22.20	70	850	700	4.60	0.09	14	120	0.035	3.09	15.91
1.73	440	2250	6	14	1.00	8.10	18.80	50	700	950	4.50	0.09	25	100	0.055	3.21	5.11
2.48	300	2900	2	7	0.53	3.80	18.40	50	550	1250	5.20	0.17	10	150	0.095	5.27	9.67
1.46	1000	2550	4	7	0.42	0.51	22.80	50	800	750	4.70	0.13	37	130	0.115	3.19	2.55
2.03	550	2800	2	4	0.60	0.02	14.20	40	1000	650	4.90	0.09	40	140	0.045	2.80	5.09
2.39	550	2550	4	12	0.61	0.02	15.20	40	1000	600	5.00	0.13	37	140	0.045	2.55	4.64

Table 28. This table shows komatiite results from a single core hole at Area C. No nickel sulphides are known in the area but the low canonical scores, high Ni/Cr and moderate to low Ni/NiP ratios suggest that it should be classified as Mineralized. The ultramafic as sampled is homogeneous, with low Cr, and shows strong similarities to Forrestania and Queen Victoria Rocks.

7.2 BARREN GROUPS WITH HIGH PERCENTAGE OF SAMPLES MISCLASSIFIED

Several areas which were designated Barren on geological grounds for the statistical analysis do not classify well as Barren using geochemical data. These areas include Area A, Yerilla and Heather Well are described and evaluated below. Each area appears to have potential for nickel sulphides, with Area A showing very good Mineralized characteristics.

7.2.1 Area A

Area A is approximately 150 km northeast of Kalgoorlie in the east-central part of the Wiluna-Norseman belt (Gee, 2975). Weathering and laterite development are typical of the Northeast Goldfields area and together with a general lack of outcrop, make geological interpretation difficult. Rocks associated with this komatiite sequence are mafic extrusive rocks and various metasediments. Area A and Area C are part of the same continuous greenstone belt.

Thirty-four samples were obtained from five diamond core holes which were drilled in a relatively small area of the ultramafic sequence. All samples were spot core taken at irregular intervals throughout the ultramafics in each hole. No evidence of sulphide mineralization was found by the initial exploration and thus the area was considered Barren for the statistical analyses. However, analysis A classified 68% and analysis B 71% of samples as Mineralized, suggesting that the original assumption that the komatiites are Barren is false. Chemically, the komatiites range from peridotites through to dunites and contain moderate to high values of Ni and Mg; moderate values of Cr and NiP and mainly low Mn (Table 29).

Hole No.	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	Ni/Cr	Ni/NiP
D	2.91	1525	2300	5	10	0.55	2.50	19.00	40	2400	1300	6.60	0.04	85	130	0.96	1.51
	1.65	788	1575	29	33	2.85	2.60	15.80	50	950	850	6.90	0.32	48	115	1.66	2.00
	2.49	900	1775	2.5	5	0.66	1.95	20.00	40	1550	650	6.00	0.07	53	110	1.14	1.97
	1.87	1088	2050	14	18	1.00	0.85	19.50	40	1200	900	6.90	0.11	68	130	1.71	1.88
	2.24	1175	1675	2.5	5	1.20	0.43	19.00	50	1800	650	8.00	0.15	85	135	0.93	1.42
	ND	2050	2325	44	53	0.74	1.55	20.00	570	950	850	5.20	0.10	108	140	ND	ND
	1.57	963	1675	2.5	5	0.90	4.00	17.60	80	1000	1650	6.10	0.11	80	125	1.68	1.74
	1.95	1613	2050	9	13	0.62	1.20	20.00	50	1450	650	5.50	0.06	88	130	1.41	1.27
C	2.26	1750	2250	28	35	0.72	1.60	19.00	40	1550	650	5.80	0.09	90	135	1.45	1.29
	2.39	150	225	129	163	8.00	7.80	14.80	70	400	1400	6.20	0.62	43	85	ND	ND
	2.15	1375	1750	9	13	0.90	1.70	19.50	30	1450	700	5.80	0.14	68	100	1.21	1.27
B	1.67	650	2600	28	35	1.00	0.33	20.60	60	1300	600	6.30	0.14	53	135	2.00	4.00
	2.24	663	2425	3	5	0.66	1.40	21.80	50	1200	1200	6.60	0.09	8	115	2.02	3.66
	2.55	425	2100	2.5	5	0.73	0.09	22.40	50	1100	950	5.60	0.06	13	140	1.91	4.94
	1.78	325	2500	13	15	0.69	0.16	21.20	70	1150	850	5.50	0.07	20	125	2.17	7.69
	2.34	288	2050	2.5	5	1.45	0.28	20.00	50	1550	900	6.30	0.20	28	110	1.32	7.11
	1.16	438	2300	5	5	1.30	0.36	20.60	70	1200	750	6.90	0.17	40	125	1.92	5.25
A	1.51	1500	2525	4	8	0.38	0.55	21.80	50	1325	600	5.00	0.06	88	115	1.91	1.68
	1.23	788	2400	11	10	1.10	0.09	21.20	50	1300	750	5.80	0.14	65	125	1.85	3.04
	3.13	100	1825	4	10	2.10	0.61	19.50	70	1850	1400	6.90	0.48	5	95	0.99	18.25
	3.89	50	575	49	73	4.30	9.95	12.80	80	1200	1850	5.20	0.85	5	70	ND	ND
	2.82	138	2450	3	8	1.65	0.26	19.50	70	1675	1200	7.10	0.26	10	125	1.46	17.75
	3.12	1125	2625	4	5	0.12	0.68	22.20	70	3100	850	5.00	0.02	45	145	0.84	2.33
	3.71	1150	2475	4	5	0.10	0.10	23.00	70	3850	850	3.90	0.02	60	175	0.64	2.15
	1.42	1463	2500	3	5	1.00	1.15	21.20	50	1200	800	5.00	0.11	100	135	2.08	1.71

Table 29. Geochemical analyses, canonical scores, Ni/Cr and Ni/NiP ratios for komatiite samples from four core holes at Area A. . This komatiite sequence is primarily peridotitic, with high Ni, moderate NiP and moderate to low Cr. Although originally considered Barren as no nickel sulphides are known to be present, there are sufficient mineralized characteristics to suggest that the area should be re-evaluated.

Detailed interpretation of the results is not possible because of the irregular sampling and absence of reliable surface geology. However, it can be suggested that the ultramafics sampled represent an intrusive komatiite suite which has a low to moderate mineralization coefficient. Nickel sulphide deposits could occur within the sequence, perhaps some distance from the areas sampled.

7.2.2 Yerilla

Yerilla is 135 km north of Kalgoorlie within a relatively small and confined greenstone belt on the southwestern side of the Keith-Killkenny lineament. The sequence appears to be metabasalts to the west overlain or intruded by a komatiite sequence which is in turn overlain by metasediments.

Thirty-two samples from three holes over a strike length of 1600 m of ultramafic were obtained. The ultramafic is a strongly magnetic olivine peridotite or dunite, is probably intrusive and contains fine-grained dispersed sulphide. Discriminant analysis A classified 28% of samples and analysis B 44% of samples as Barren. The canonical scores (Table 30) are clustered in the low coefficient of mineralization range and the komatiite sequence appears to have more Mineralization than Barren characteristics. Chemically, the ultramafics contain moderate to high Ni, Cu and Cr and moderate to low NiP (Table 30).

The geochemical results suggest that the Yerilla komatiites were derived from a komatiitic magma which contained nickel sulphides, but that the komatiites sampled are some distance removed from any nickel sulphide accumulations.

Depth Meter	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	Ni/Cr	Ni/NiP
125	410	3.02	400	1500	26	40	2.80	3.95	13.00	80	2300	1200	6.90	0.34	35	110	0.65	3.75
	430	2.58	662	2000	20	30	2.00	1.65	17.10	60	2250	900	6.90	0.23	50	120	0.89	3.02
	450	2.40	550	2250	24	25	1.50	0.15	17.10	60	2350	1050	6.80	0.17	35	120	0.96	4.09
	470	2.61	762	1900	22	28	1.10	3.10	16.00	40	1600	1000	5.80	0.12	40	105	1.19	2.49
	490	2.57	475	2200	8	10	1.10	0.50	18.20	40	1600	1150	5.50	0.06	35	120	1.38	4.63
	510	2.18	900	2150	20	25	0.69	1.25	17.10	40	1200	900	5.20	0.07	40	110	1.79	2.39
	530	2.22	525	2350	18	15	0.53	1.05	19.90	40	1250	950	5.80	0.07	30	120	1.88	4.48
	550	2.11	450	2375	8	8	0.61	1.10	19.40	50	1300	800	5.50	0.07	30	125	1.83	5.28
	570	1.39	675	2350	10	10	0.56	0.50	19.40	50	900	900	5.50	0.07	25	110	2.61	3.48
	590	2.79	200	2450	16	28	0.59	0.85	21.10	40	1150	900	5.20	0.07	15	110	2.13	12.25
	610	2.20	1262	2200	36	35	0.61	0.70	18.80	40	1600	1150	5.50	0.11	50	110	1.38	1.74
	630	2.63	425	2550	2	5	0.95	1.40	21.70	40	1200	1000	6.60	0.11	20	140	2.13	6.00
	650	1.90	500	2575	2	5	0.95	0.70	20.00	100	1400	1000	6.90	0.11	20	140	1.84	5.15
	670	2.97	600	2325	2	5	1.04	1.25	19.40	40	1750	800	7.20	0.14	40	150	1.33	3.88
	690	3.38	375	2100	8	18	0.79	0.95	19.40	40	1900	1300	8.00	0.20	23	130	1.10	5.60
	710	2.65	775	2200	8	13	1.50	0.80	20.00	40	2000	1050	6.60	0.11	45	130	1.10	2.84
	730	3.34	600	2150	4	15	1.40	2.10	19.40	40	1900	1200	7.20	0.09	43	140	1.13	3.58
	750	2.51	612	1975	38	55	1.80	2.10	18.20	60	1700	900	5.90	0.14	40	120	1.16	3.22
	770	2.43	800	1900	20	20	1.65	3.40	16.00	60	2300	1100	6.60	0.23	50	110	0.83	2.38
	790	2.22	850	1900	28	25	1.80	4.25	16.00	40	1300	1100	5.80	0.23	73	125	1.46	2.23
247	810	2.50	612	1900	42	45	1.80	5.20	14.50	50	1800	1300	6.60	0.18	40	100	1.06	3.10

Table 30. Representative komatiite sample results from a single core hole at Yerilla. These results show some Mineralization characteristics - moderate to high Ni and moderate Cr with canonical scores in the low mineralization coefficient range extending into the Barren range. There is insufficient data available to determine whether the sequence is volcanic or intrusive and whether it should be regarded as Mineralized or Barren.

7.2.3 Heather Well

Heather Well represent an intrusive komatiite suite 7 km in length and 0.1 to 0.8 km in width approximately 75 km northwest of Leonora (Fig. 78). This part of the Leonora-Wiluna greenstone belt is characterized by elongate, domal granitic plutons and batholiths. The latter intrude and deform the Archaean volcanogenic succession which consists of tholeiitic basalts, intrusive and extrusive komatiites, felsic volcanics, volcanogenic sediments, arenaceous and conglomeratic sediments and minor banded iron formations. The belt is further characterized by north-northwest trending tectonic lineaments that were active throughout the deposition of the volcanogenic succession.

Two core holes were drilled through the east contact of the ultramafic into amphibolites at Heather Well (Fig. 56). Core samples were taken at 1.5 m intervals throughout the ultramafic. Total number of samples was 101, and 92 were used in the statistical analysis. There was no evidence of nickel sulphides at Heather Well and the komatiite sequence was originally considered as Barren.

The discriminant analyses did not confirm the Barren classification. In analysis B, 40% of Heather Well samples were classified Barren and the remaining 60% were Mineralized. These classifications reflect the higher mean values for NiP (733 ppm) and Ni (1936 ppm), and lower values for Cr (1293 ppm) and Mn (762 ppm) than the respective mean values for all Barren groups (Table 3). Complete geochemical results are given in Table 31. There are several very distinct chemical trends throughout the hole sampled. Ni and Mg decrease with depth while Cu, Al, Zn, Cr, Mn and Fe and TiO_2 all show erratic but definite increases with depth (Fig. 57). These trends indicate that the base of the komatiite sequence is west of the drill hole collar and that the hole is probably penetrating increasingly younger komatiites with depth.

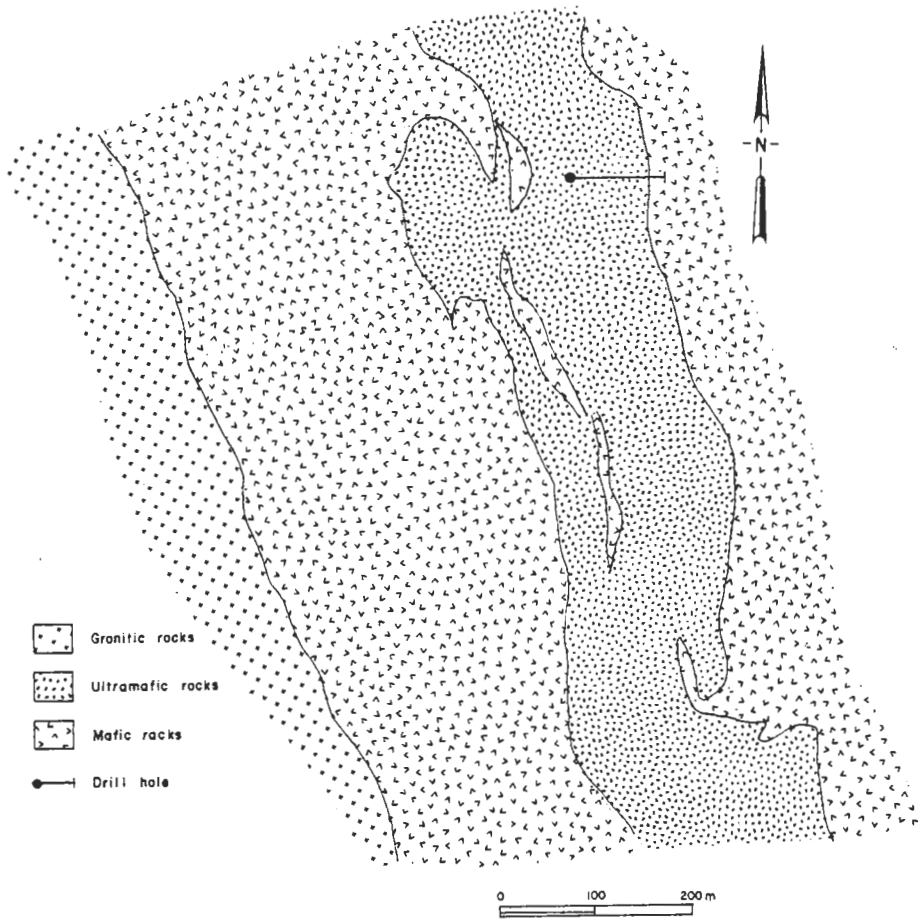

Fig. 56 . Interpretive geology of the Heather Well area showing location of the hole sampled.

Discontinuities occur within the komatiite sequence at depths of 139, 175, 200, 225, 229m (Fig. 57 and Table 31). The section below 200 m shows a consistent Barren classification and represents an unknown number of relatively thin (2 to 12 m thick) komatiites. Between 139 and 175 m the komatiite has a low to high mineralization coefficient and may be either an individual komatiite unit or part of a much thicker unit. The relatively regular decrease in Ni and Mg between 93 and 192 m suggests that this section of the hole may be a single komatiite. The increase in Cu is very marked in the lower part of the hole (Fig. 57) but does not coincide exactly with the decrease in Ni or the increase in Cr. Whereas Ni, Cu and Cr all show sharp changes, Mg decreases gradually with depth.

Two main conclusions can be drawn from the canonical scores and geochemical results.

1. The basal part of the komatiite sequence which is usually regarded as the most favorable section for nickel sulphide accumulation, was not tested by the drill hole.
2. The overall mineralization coefficient for the hole is positive but relatively low and possibly indicates that the sequence as a whole is favorable but that the section sampled is not in close proximity to nickel sulphides. Comparison with forrestania results support this conclusion.

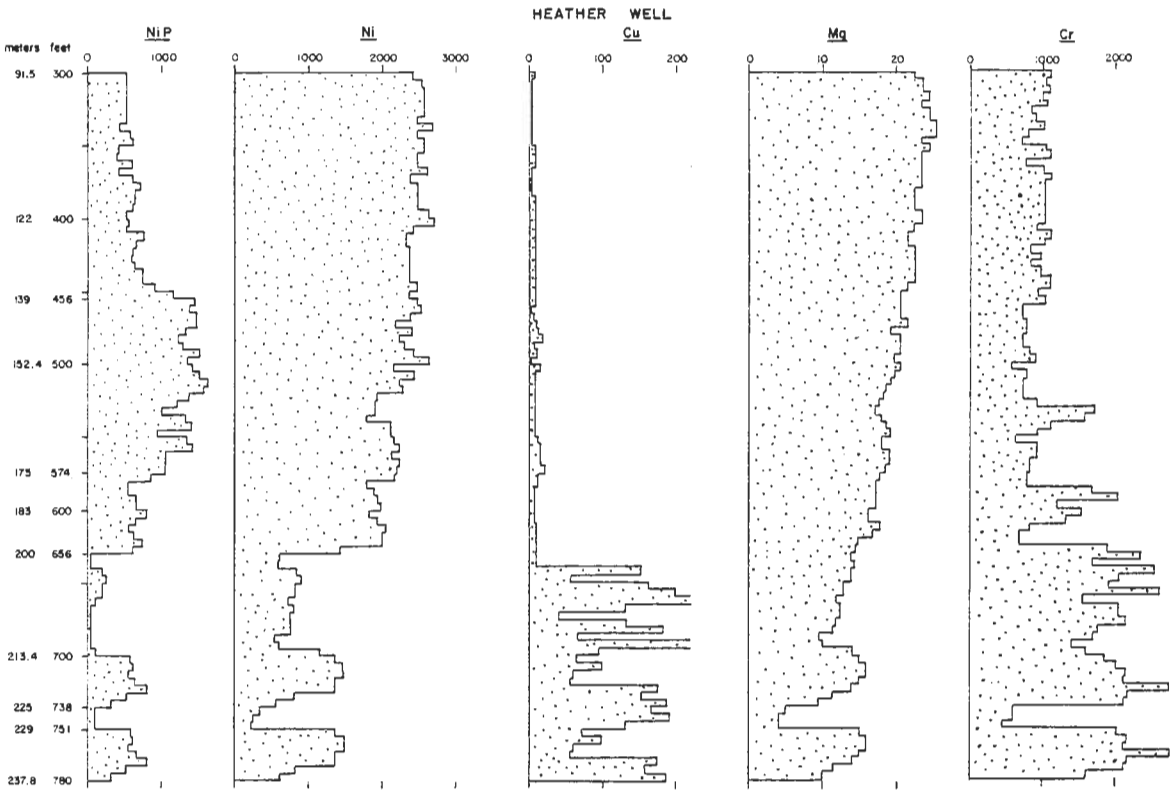

Fig. 57. Histogram of NiP, Ni, Cu, Mg and Cr geochemical results for Heather Well. Note the decrease in Ni and Mg and the increase in Cu and Cr with depth which suggests that the hole is penetrating upwards through a komatiite ultramafic sequence. Vertical dimension not to scale.

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co
93	305	2.42	538	2425	4	10	0.38	0.20	23.20	40	1150	550	4.40	0.13	23	115
	310	2.04	563	2575	4	5	0.35	0.27	24.40	40	1100	600	3.60	0.04	25	115
	315	1.95	538	2600	4	5	0.40	0.18	24.10	40	1150	550	3.60	0.02	25	110
	320	2.10	525	2600	3	5	0.25	0.20	24.80	40	1050	600	3.40	0.02	25	110
	325	1.97	550	2550	4	5	0.27	0.10	24.10	40	1100	550	3.40	0.02	25	110
	330	2.08	525	2550	4	8	0.26	0.10	24.60	40	900	550	3.30	0.02	25	115
	335	2.21	563	2475	3	8	0.32	0.12	24.80	40	950	550	3.40	0.02	25	115
	340	2.33	563	2675	2.5	8	0.36	0.10	25.60	40	1050	600	3.40	0.02	28	115
	345	1.99	438	2475	3	8	0.30	0.13	25.60	40	950	550	4.30	0.02	28	115
	350	1.66	600	2525	3	8	0.38	0.09	24.40	40	750	550	3.10	0.04	25	105
	355	2.14	625	2500	4	10	0.31	0.07	25.20	40	1120	550	3.20	0.04	25	105
	360	2.21	450	2475	5	10	0.27	0.03	24.40	40	1150	550	3.90	0.04	25	105
	365	2.11	400	2525	2.5	8	0.32	0.09	24.40	40	900	550	4.00	0.04	25	115
	370	1.84	575	2650	3	5	0.32	0.07	24.40	40	1050	550	3.20	0.04	25	105
	375	2.05	438	2375	3	5	0.36	0.09	24.40	40	1150	500	3.90	0.04	28	110
	380	1.93	625	2500	3	5	0.22	0.07	24.10	40	1050	500	3.60	0.02	28	110
	385	2.16	725	2525	3	5	0.21	0.45	22.80	40	1050	550	3.60	0.02	25	110
	390	2.75	575	2500	3	8	0.21	0.38	23.80	30	1050	600	3.60	0.02	25	115
	395	2.60	575	2575	3	8	0.21	0.20	23.20	30	1050	600	3.80	0.02	28	115
	400	2.44	625	2625	3	8	0.20	0.13	24.10	40	1050	550	3.50	0.02	28	120
	405	2.28	513	2725	3	8	0.40	0.29	23.80	40	1050	600	3.40	0.05	28	120
	410	2.28	563	2450	3	8	0.59	0.24	22.90	30	950	500	4.20	0.05	28	115
	415	2.50	550	2350	3	8	0.69	0.12	22.20	30	1150	500	4.30	0.05	33	120
	420	2.12	763	2375	3	4	0.76	1.15	22.20	30	1050	650	3.40	0.10	25	125
	425	2.21	563	2400	3	8	0.45	0.35	23.20	30	950	550	3.40	0.04	25	105
	430	2.36	625	2450	3	8	0.37	0.12	22.80	40	1000	550	4.80	0.04	25	115
	435	2.33	588	2375	3	8	0.33	0.18	23.20	30	950	550	3.40	0.04	25	105
	440	2.29	550	2375	3	8	0.30	0.10	22.80	30	1000	500	4.10	0.04	25	105
	445	2.39	763	2500	3	8	0.36	0.09	22.20	30	1150	450	3.40	0.04	23	100
	450	1.52	925	2375	6	4	0.49	0.93	21.00	30	950	750	4.00	0.04	23	95
139	455	2.30	1175	2475	3	8	0.46	0.41	21.10	30	1050	650	4.60	0.04	15	105
	460	1.52	1463	2550	6	12	0.36	0.22	21.30	30	750	650	4.50	0.04	25	125
	465	2.13	1400	2400	6	16	0.29	0.48	21.30	30	750	850	4.10	0.02	75	140
	470	1.62	1500	2225	11	20	0.36	0.70	21.00	40	800	950	4.20	0.04	60	115
	475	1.53	1475	2450	6	8	0.33	0.37	22.20	30	800	800	3.60	0.04	53	115
	480	1.90	1338	2275	5	12	0.38	0.70	19.40	30	950	800	3.20	0.04	48	105
	485	1.12	1225	2300	3	4	0.36	0.22	21.00	40	750	700	3.60	0.05	48	110
	490	1.55	1300	2475	10	16	0.31	0.10	21.00	40	650	750	3.60	0.02	40	110
	495	1.79	1525	2675	6	12	0.39	0.22	21.00	40	950	700	3.40	0.02	58	125
	500	1.35	1375	2150	6	8	0.24	0.10	20.20	30	800	800	4.00	0.04	53	105
	505	1.30	1413	2475	13	12	0.36	0.09	21.00	40	800	700	3.40	0.04	55	125
	510	1.32	1525	2250	10	8	0.33	0.33	20.20	40	750	850	4.50	0.04	55	115
	515	1.00	1650	2300	9	8	0.25	0.10	19.80	40	750	850	4.90	0.04	53	120
	520	1.42	1575	1350	11	12	0.24	0.41	18.90	40	750	850	4.90	0.04	68	125
	525	1.85	1388	1925	9	8	0.43	0.18	19.40	30	950	750	4.60	0.04	53	125
	530	2.93	1225	1925	6	8	0.60	0.30	18.00	30	1750	750	4.50	0.04	60	130
	535	3.22	988	1800	5	8	0.53	0.30	17.60	20	1600	650	4.60	0.04	50	120
	540	2.43	1350	2125	6	12	0.49	0.75	18.40	30	1150	650	2.80	0.05	53	110
	545	2.12	1438	2275	14	16	0.33	1.37	18.90	30	950	600	2.90	0.02	53	105
	550	1.74	975	2150	11	16	0.33	0.35	19.40	30	850	550	3.20	0.02	38	120
	555	2.15	1338	2175	10	16	0.42	0.63	18.40	30	950	600	3.00	0.02	50	100
	560	1.89	1438	2250	10	24	0.36	0.18	19.40	40	950	500	3.10	0.02	50	100
	565	2.00	1063	2150	10	12	0.31	0.22	19.40	30	850	600	3.30	0.04	43	110
	570	2.01	1088	2275	9	12	0.33	0.18	19.60	30	850	650	3.40	0.02	45	115
175	575	1.71	1053	2225	8	8	0.31	0.30	19.10	30	800	600	3.30	0.02	43	105
	580	1.97	363	2220	9	8	0.40	0.66	19.00	30	800	700	4.10	0.04	43	120
	585	3.60	550	1300	6	8	0.38	1.05	17.60	20	1700	750	4.80	0.08	38	120
	590	3.58	563	1900	6	8	0.30	0.90	17.20	20	2050	550	5.90	0.07	35	115
	595	2.64	588	1950	9	8	0.30	0.33	17.60	20	1200	600	5.20	0.07	43	115
192	600	3.41	575	2000	8	16	0.38	0.33	17.60	20	1550	600	5.40	0.08	40	125
	605	3.11	800	1825	9	12	0.30	2.30	16.30	20	1350	650	5.00	0.07	45	110
	610	2.13	663	1950	8	12	0.90	1.40	16.50	30	850	550	5.50	0.13	40	115
	615	1.83	650	2075	8	12	1.05	1.00	17.80	30	700	550	5.00	0.11	33	115
	620	1.81	825	2025	8	12	1.05	1.30	17.00	30	700	550	4.50	0.08	33	105
	625	2.95	750	2025	8	12	1.15	5.20	15.10	40	1900	750	5.50	0.19	48	115
	630	3.57	813	1450	8	16	2.25	5.60	14.70	40	2350	900	5.50	0.14	38	105
	635	4.10	25	575	3	4	5.00	2.35	13.90	30	1700	650	6.00	0.30	8	95
	640	4.70	25	600	2.5	4	4.40	2.61	14.50	70	2450	650	5.30	0.11	8	95
	645	3.61	200	875	163	152	3.50	4.30	12.90	70	2050	800	5.30	0.16	25	95
	650	3.26	250	900	50	56	3.30	4.50	13.90	80	1900	800	5.50	0.19	23	95
	655	4.23	238	825	188	164	3.50	6.00	13.10	80	2600	950	6.30	0.40	20	95
	660	3.81	213	825	126	200	3.40	6.20	13.50	60	1650	900	5.30	0.44	20	90
	665	ND	100	725	474	5960	3.65	8.20	12.10	50	2050	950	4.40	1.50	13	85
	670	4.33	50	800	189	132	4.30	6.35	12.50	70	2050	950	4.80	0.56	8	95
	675	4.45	25	775	38	40	4.30	7.40	12.30	110	2150	1150	4.70	0.47	5	85
	680	4.10	38	775	155	132	4.20	7.40	11.90	100	1750	1100	4.70	0.47	5	80
	685	ND	50	750	406	184	4.20	7.00	11.50	110	1720	1000	5.30	0.47	5	100
	690	5.32	38	525	50	68	4.80	7.15	9.50	40	1400	900	7.40	0.50	8	110
	695	ND	25	600	706	7700	4.70	6.85	10.30	90	1600	1050	6.80	3.56	8	110
	700	4.41	94	1150	88	96	2.60	2.68	13.90	50	1850	900	7.10	0.35	13	130
	705	3.30	538	1375	64	72	2.10	2.10	15.40	50	2000	900	7.10	0.23	45	130
	710	2.96	600	1475	93	100	2.00	1.40	15.80	70	2150	1100	7.10	0.23	48	130
	715	3.29	550	1475	46	60	1.85	1.63	15.80	50	2100	950	7.10	0.23	48	130
	720	3.37	638	1375	44	56	1.85	1.40	15.00	70	2750	1050	7.00	0.23	50	130
	725	3.07	800	1350	164	176	2.40	2.28	13.90	70	2150	950	7.80	0.30	68	140
	730	3.26	500	800	133	156	3.30	5.50	11.50	100	2100	1350	9.20	0.44	55	125
	735	3.23	300	575	154	188	5.10	5.29	9.50	150	1600	1550	8.10	0.44	40	105
225	740	3.53	75	325	138	168	7.00	7.00	5.10	130	600	2150	7.70	0.80	13	100
	745	3.29	75	225	183	192	7.30	7.00	3.90	170	450	2200	7.70	0.90	23	100
229	750	ND	63	200	101	132	7.55	7.40	3.80	370	400	2200	7.80	0.78	15	95
	755	3.29	538	1375	64	72	2.10	2.10	15.40	50	2000	900	7.10	0.23	45	130
	760	2.96	600	1475	93	100	2.00	1.40	15.80	70	2150	1100	7.10	0.23	48	130
	765	3.29	550	1475	46	60	1.85	1.63	15.80	50	2100	950	7.10	0.23	48	130
	770	3.37	638	1375	44	56	1.85	1.40	15.00	70	2750	1050	7.00	0.23	50	130
	775	3.07	800	1350	164	176	2.40	2.28	13.90	70	2150	950	7.80	0.30	68	140
238	780	3.29	500	800	133	156	3.30	5.50	11.50	100	2100	1350	9.20	0.44	55	125

Table 31 . Geochemical analyses and canonical scores (B) for a continuous section of 145 m. of komatiite at Heather Well. Samples are drill core selected at approximately 1.5 m. intervals. True thickness of komatiite sampled is approximately 120 m. Geochemical trends for NiP, Ni, Cu, Mg and Cr are illustrated in Fig. 51. The outstanding feature of these results, illustrated by the Ni, Cu, Mg and Cr values, is the definition of a 100 m. thick, extremely evenly differentiated intrusive komatiite, overlain by much thinner and lower Mg and Ni, komatiites. The significance of the increase in NiP (and thus S) results towards the center of this main unit is unknown.

CHAPTER 8

8. DISCUSSIONS AND CONCLUSIONS

This study has demonstrated that komatiites associated with nickel sulphide mineralization can be distinguished geochemically from barren komatiites. It has also provided a wealth of data which may assist others in speculating on the origin of komatiites and nickel sulphide deposits.

8.1 MEAN GEOCHEMICAL VALUES

The mean element and trace metal values for Western Australian komatiites, exclusive of high Mg basalts, as determined by this study are as follows: Ni 1875 ppm; Cu 40 ppm; Zn 72 ppm; Cr 1930 ppm; Mn 1090 ppm; Co 129 ppm; Al 1.9%; Ca 2.5%; Mg 17.8%; NiP 720 ppm; CuP 32 ppm; CoP 40 ppm. All analyses are on a volatile included basis. Chromium is understated (the extraction was not always total and some very high Cr bearing komatiites were excluded) and the mean Cr value is probably of the order of 2500 ppm. For comparison with the above values, Levinson (1974) quotes the following as average values in ultramafic rocks: Co 150 ppm; Cr 2000 ppm; Cu 20 ppm; Mn 1300 ppm; Ni 2000 ppm; Zn 50 ppm. Cameron et al. (1970) list mean values for the partial determinations of Cu (CuP), Ni (NiP) and Co (CoP) for 1079 Canadian ultramafic samples as 171 ppm; 1048 ppm and 57.6 ppm respectively.

8.2 MINERALIZED AND BARREN KOMATIITE CHARACTERISTICS

Komatiites which host nickel sulphide deposits have geochemical signatures which differ significantly from komatiites which are Barren. No single element or chemical determination is diagnostic, but collectively, Cr, Ni, Zn, Cu, NiP, Mg, Fe and Co distinguish between the two groups of komatiites. In many instances if values for Zn, Cu, Mg and Fe approximate the mean values of komatiites, Cr, Ni and NiP are sufficient to differentiate between Mineralized and Barren groups.

Discriminant analysis is an effective method for separating Mineralized and Barren komatiites using the equation and constants outlined below:

$$D = 0.30\,(NiP) - 0.99\,(Ni) - 0.40\,(CuP) + 0.54\,(Cu) - 0.23\,(Al) + 0.10\,(Ca) - 0.70\,(Mg) - 0.91\,(Zn) + 1.32\,(Cr) + 0.09\,(Mn) - 0.67\,(Fe) - 0.36\,(CoP) + 1.92\,(Co)$$

where, if the discriminant score D for any sample is such that D is greater than Do, then the sample is Barren and if the score is less than Do the sample is Mineralized (see also Section 3.2 for a more detailed description). Do is equal to 2.55. A mineralization coefficient has been defined where samples with scores between 2.55 and 2.13 have a low coefficient (of mineralization); samples between 2.13 and 1.72 have a moderate coefficient; samples between 1.72 and 1.30 have a high coefficient; and below 1.30 the coefficient is very high. If the geology of a komatiite sequence is known, discriminant scores can be used as a mineralization index to provide a proximity guide for nickel sulphide accumulations.

It is preferable that samples should only be grouped if it can be demonstrated that they represent an individual komatiite unit, either intrusive or extrusive. Individual sample results may be difficult to interpret because of the heterogeneous nature of individual komatiites and the

chemical changes caused by serpentinization and talc carbonate alteration. Ideally, samples should be obtained across the complete width of a komatiite, but if this is not possible, it is preferable to sample a width of five to ten meters with a minimum of five samples.

Correlation analysis confirmed the following chemical relationships which are of fundamental significance to the komatiite suite. As Ni, Ni$\underline{P}$, Mg, Co$\underline{P}$ and Co increase, Al, Cu, Zn, Mn and Fe decrease; as Ni increases so does Mg but Al decreases. Other points of note are most correlations are much stronger in Barren komatiites than in Mineralized komatiites; and the chalcophile elements show moderate to strong correlations with silicate mineral elements in Barren komatiites but only weak or no correlations in Mineralized komatiites. These correlation differences have been interpreted to mean that in Mineralized komatiites the chalcophile elements, Ni, Cu, Co and some Fe are held in part as a sulphide fraction and/or a part of the sulphide phase has been concentrated and removed from the system as an immiscible sulphide - oxide melt. The relatively strong correlations between the chalcophile elements and silicate mineral elements in Barren komatiites suggests that the chalcophile elements are held in the silicate lattice in these komatiites.

A strong negative correlation exists between Cu and Mg in certain instances (Fig. 14 - Kambalda). This may indicate that during strong carbonate alteration Ca is added and Mg is removed from the system.

Cameron et al. (1971) after a study of certain chemical determinations from a suite of ultramafic rocks associated with nickel deposits in Canada, considered that ore and barren ultramafics could be distinguished primarily on their sulphur and leachable copper (Cu$\underline{P}$) contents. In addition, they

concluded that there was enrichment of CuP, NiP and S and to a lesser extent CoP, in untramafics associated with ore deposits compared to barren ultramafic rocks. If values for CuP, NiP and S exceeded 100 ppm, 1780 ppm and 0.178% resepctively, the ultramafic in question could be regarded as having high ore potential. The present study of Western Australian komatiites indicates that high NiP and S values are encouraging but not diagnostic. Only the Weebo Bore komatiite had a mean CuP value of more than 100 ppm and high CuP values are not necessarily indicative of nickel sulphide mineralization in Western Australian nickel provinces. Some of the Canadian nickel sulphide deposits included in the Cameron et al. (1971) study differ very substantially in metal content to Western Australian deposits. Whereas Western Australian deposits have ni to Cu ratios of 8 to 400, the Canadian deposits for which information is given (Table II, Cameron et al, 1971) range from 1 to 5.5. Thus, copper is much more prevalent in the Canadian deposits which may explain the fact that Cu is apparently diagnostic in Canada, but not in Western Australia. A more detailed evaluation of the Cameron et al. (1971) data (their Table IV) reveals a very wide range in CuP values with some of the examples such as Alexo, Preissac, Puddy Lake, Langmuir, Texmont, Marbridge and Bucko falling within Western Australian komatiite CuP ranges. Most but not all Western Australian komatiite ore hosts contain more than 0.07% sulphur close to mineralization but may have lower contents remote from mineralization. Sulphur appears to have been introduced to some ultramafics at a late stage in their geologic history and barren komatiites in this study may contain up to 2% sulphur.

Naldrett and Arndt (1976) suggested that komatiites containing more than 40 wt. percent MgO (volatile free basis) are more likely to host sulphides than those with less than 40%. In a general sense this is true as a large proportion of komatiites in any province are thin units or thin komatiite lavas with low mean MgO. These units do not host nickel sulphides.

However, economic nickel deposits are associated with komatiites (Unit A - Windarra South) with mean MgO contents as low as 30% (volatile included) and the hosts in a majority of volcanic associations contain less than 36% MgO (volatile included). In addition, within any volcanic komatiite host, MgO will often vary from 32-38% in the cumulate portion to 20-25% in the former silicate liquid fraction. Magnesium is thus useful in a negative sense, in that if within any komatiite pile peridotites are absent, the area can be regarded as non-prospective.

Although Mg on its own is not diagnostic the Ni/Mg ratio is significant. Peridotitic komatiites (those komatiites with moderate to high Mg) which are Barren often contain relatively low Ni and Ni/Mg ratios for these komatiites are usually less than 80 and may be as low as 50. Mineralized komatiites usually have Ni/Mg ratios of approximately 100.

None of the previous studies of ultramafic rocks and nickel deposits have recognized the importance of chromium in determining prospectiveness. The present study suggests that chromium is of paramount importance and that any komatiite, whether of the volcanic or intrusive suites, will be relatively low in chromium and high in nickel if it contains or is spatially associated with nickel sulphides. The nickel to chromium ratio is always greater than one (1) in mineralized komatiites. Most of the Cr in mineralized komatiites is present in a form which is acid leachable, whereas in barren komatiites some chromium occurs in non-acid leachable form which suggests there is less chromite in mineralized komatiites. However, the important conclusion reached is that there is less Cr in the silicate mineral lattice in Mineralized komatiites than in Barren komatiites. This appears to be a diagnostic difference between the two groups of komatiites.

8.2.1 Volcanic Suite

Volcanic komatiite associations consist of a suite of ultramafics ranging from high Mg olivine peridotite or dunite to low Mg proxenites and high Mg basalts. The komatiites in this suite can be divided into two broad divisions called thick units and thin units. Thick units occur near or at the base of a typical komatiite pile and comprise the lower one-third of the pile whereas thin units comprise the upper two-thirds. However, some komatiite piles contain no thick units and in others, thick units appear to dominate. Within a typical pile Ni, Mg, NiP and CoP tend to increase and Cr, Al and Cu tend to decrease towards the base. Cobalt remains constant. Zn, Mn and Fe are erratic but in some instances Zn shows an increase and Mn and Fe decrease towards the base of the sequence. These overall trends are severely modified by strong trends within individual komatiites.

Thick and thin units both show similar chemical and mineralogical zoning across individual komatiites. This zoning is a primary differentiation feature probably caused in part by flow differentiation and by crystal settling after extrusion. Differentiation causes the development of an olivine cululate lower portion and on upper silicate liquid portion which contains few if any olivines, within each volcanic komatiite unit. In a thick unit the lower olivine cumulate section usually averages 20% Mg and comprises two-thirds to three-quarters of the komatiite unit. In a thin unit the olivine cumulate section would contain more interstitial silicate liquid and thus a lower Mg content - usually between 14% and 18%. In addition the olivine cumulate section and silicate liquid portion each comprise approximately 50% of any thin unit komatiite.

Complete geochemical profiles through thick units at Kambalda, Bouchers and Windarra South show that values for Ni, NiP, Mg and CoP consistently increase and Cr decreases toward the base of each unit. Magnesium often has a maximum value in the center or just below the center of the unit. The changes in Ni and Mg reflect the gradation in rock type from spinifex textured pyroxene peridotite at the top to equant olivine textured peridotite or olivine peridotite in the lower part of the unit. A thin (0.25 m) pyroxenitic (silicate liquid) chilled contact zone may be present at the base.

In many volcanic sequences metamorphism and/or alteration has completely obliterated the original mineralogy and texture and individual komatiites in the sequence cannot be separated using these criteria. However, it has been demonstrated in this study that in highly metamorphosed sequences the internal structure of komatiite sequences can be defined by chemistry. Examples are Windarra South and Bouchers (4.1.2 and A.3.1). The mineralization coefficient of a thick unit must be determined from the olivine cumulate section of the komatiite. The pyroxenitic or pyroxene peridotite, silicate liquid derived upper portion, which may vary from 1 to 10 m in thickness, will always show a lower mineralization coefficient than the cumulate section (due to higher Cr and lower Ni content) and in some cases may indicate that unit is Barren. Average chemical values for the cumulate section of a thick unit with a moderate to high mineralization coefficient are: NiP 1000 ppm; Ni 2100 ppm, Cu and CuP 30 to 90 ppm; Al 1% to 2%; Ca 0.1% to 3%; Mg 17% to 24%; Zn 60 ppm; Mn 1000 ppm; Cr 1300 ppm; Fe 5.5%; CoP 55 ppm; and Co 120 ppm. In general, if NiP or Ni are less than 500 and 1800 ppm respectively, or Cr greater than 2100 ppm, the unit can be regarded as Barren. With higher Ni, Cr can also rise and the unit still be classified as Mineralized. As was pointed out earlier, the Ni to Cr ratio should always exceed one.

A Barren komatiite would contain less NiP, between 50 and 1200 ppm; a Ni content of 1000 to 1500 ppm, although in some Barren units Ni contents reach 2500 ppm; and a Cr content of between 1500 and 5000 ppm. Examples of Barren thick units occur at Red Well where peridotites contain typical values as follows: 20% Mg, 2400 Ni, 2200 Cr and 200 ppm NiP to rocks with very low Ni (1200 ppm) and high Cr (5000 ppm). However, NiP is consistently low indicating very little sulphur was available to the original magma. At Yilmia some thick units average 18-20% Mg, 1200-1500ppm Ni, 2200-3000 ppm Cr and up to 600 ppm NiP. Other examples occur at Wongi South, Eureka, Mt. Step, Collin Well etc.

Thick units range up to 60 m in width, but average width is probably of the order of 25 m. With widths of less than 15 m, the Mg content of both the cumulate sections and the unit as whole, decreases. The thick units are almost invariably present at the base of a pile and are not scattered throughout the sequence as would be expected if they were intruded. The volcanic suite lava piles show definite trends in chemical composition from top to bottom suggesting that the most magnesium rich lavas leave the magma chamber at depth first, followed by pulses of successively less Mg and S rich magma. The sedimentary environment into which the komatiites were extruded is assumed to be marine and quiesant, which allowed the deposition of persistant but thin horizons of chemical, sulphide rich sediments (Ross & Hopkins, 1975). These shales often separate individual thick units and show no evidence of severe disruption which should have been caused by the intrusion of komatiite magma. The sequence of events in an ideal situation appears to have been extrusion of a thick unit in a marine environment followed by a quiesant period with chemical sediment deposition. Further thick units were then extruded followed by progressively thinner units and ultimately in some instances by high Mg basalts.

8.2.2 Intrusive Suite

Intrusive suite komatiites are more homogeneous, have higher mean Mg and Ni and lower Cu contents than volcanic suite komatiites. An intrusive sequence may range up to 1000 m in width and usually consists of one or more separate and perhaps semi-contemporaneous intrusive komatiite units. Individual komatiites usually consist almost entirely of peridotite or dunite derived from an olivine cumulate liquid. In some instances there is evidence of in-situ or flow differentiation with less Mg rich rocks near contacts. However, even the less Mg rich rocks contain equant olivines and it is doubtful that an olivine free, silicate liquid portion existed in the magma at the time of intrusion.

Holes 4 and 5 from Forrestania illustrate the chemical variation across an intrusive komatiite. In general there is much less chemical variation than is present across a thick unit, volcanic komatiite. For example in hole 5 Forrestania, Cr, Ni, Mg, TiO_2, Mn and Fe are relatively constant across the entire width of the komatiite. In hole 4 Forrestania Mg is at a maximum near the centre of the komatiite.

Mean Mg and Ni contents are probably of the order of 22% and 2300 ppm respectively as compared to mean Mg and Ni values for thick units of approximately 19-20% and 2000 ppm.

In the Leonora-Wiluna Nickel Province the intrusive komatiites are spatially related to a major crustal fault system, but no evidence of a similar relationship has been published for the Forrestania Province.

Intrusive suite komatiites with a high mineralization coefficient have the following approximate chemical values: NiP 1200 ppm; Ni 2500 ppm; Cu 5 to 60 ppm; Al 0.5%; Ca 0.5% to 2%; Mg 20% to 26%; Zn 60 ppm; Cr 1000 ppm; Mn 900 ppm; Fe 6%; CoP 60 ppm; and Co 125 ppm. Forrestania hole 4 intersected both

mineralized and barren komatiites. The barren komatiite has a mean Mg content in excess of 20% but very low Ni (approximately 1000 ppm) and high Cr (approximately 3000 ppm). Marvel Lock C is a further example of a barren intrusive komatiite. It contains 21% to 22% Mg but only 1750 (average) ppm Ni and 3000-4000 ppm Cr.

Intrusive association komatiites, whether mineralized or barren, may have substantial sections which are very low in Cu (5 ppm or less), whereas mineralized thick units of the volcanic suite seldom have less than 30 to 40 ppm Cu. The silicate liquid-olivine crystal ratio is lower (i.e. there was less silicate liquid) in intrusive komatiites than in thick units of the volcanic association.

8.2.3 Application of Mineralized-Barren Criteria

In Chapter 6 it was shown that the komatiites in the Forrestania and Southern Cross sections respectively of the Southern Cross-Forrestania greenstone belt had significantly different chemical character. In addition with a relatively small program of komatiite sampling, most komatiites in the Southern Cross section of the belt were shown to be Barren. The chemistry of Southern Cross komatiites indicated that a nickel province with the potential of the Forrestania Nickel Province did not exist.

In Chapter 5, komatiite geochemistry was used to show that komatiites in the Wonganoo-Bandjawarn greenstone belt were predominantly from the volcanic suite. In addition, although thick units were present, some with moderately favorable chemistry, it could be concluded that the greenstone belt as a whole did not have significant potential for moderate to large nickel sulphide deposits.

In Chapter 7, Mineralized-Barren chemical criteria were applied to two "new" areas. One area called Area C, contained komatiites which had similar chemistry to both Forrestania and Queen Victoria rocks. Mg values averaged 22%, Ni 2500 ppm, Ni/Cr ratios 3.0 and Ni/Ni$\underline{P}$ ratios 2.5-3.0. These results suggest that this area is very prospective for large nickel sulphide deposits.

8.3 CHEMICAL GRADIENTS

The problem of chemical gradients relative to nickel sulphide deposits is compounded by the heterogeneous nature of volcanic komatiite suites. At Windarra South there is a suggestion that the komatiite hosts have a lower coefficient of mineralization with distance along strike and down dip from the main sulphide accumulations. A similar relationship is evident at Bouchers. However, in both cases there is a need for additional data before a chemical gradient could be established without question.

At Forrestania, in an intrusive association, hole 5 which is several kilometers south of the mineralized zone in hole 4, has a lower coefficient of mineralization than hole 4. In an intrusive sequence of linear, semi-continuous komatiites such as Forrestania, it is apparent that the komatiites show mineralization characteristics over long strike lengths and across most of the width of the sequence. The forrestania data suggests that this sequence could be shown to be mineralised if it was systematically sampled anywhere along a strike length in excess of 30 kilometers. Within volcanic suites much more detailed sampling would be required because of the heterogeneous nature of the sequence, both in cross section and along strike. However, even within volcanic suites, in areas of major mineralization such as Kambalda, there are sufficient mineralized thick units present for very widespread (along strike) sampling traverses to have been effective, as long as particular care was taken to obtain samples from basal komatiite units.

8.4 REGIONAL AND STRATIGRAPHIC CHEMICAL DIFFERENCES

Discriminant analysis D (Fig. 5) suggests that there are regional and stratigraphic chemical and geochemical differences between komatiites. These differences are minor in terms of individual metal or element values but appear to be real and significant. The concept of nickel provinces also supports regional chemical differences in komatiites. Komatiite magmas which were generated in different areas of Yilgarn Block and at slightly different periods of time had differing mean chemical compositions. The main differences appear to have been in magnesium content and trace element values of S, Ni, Cr and Cu. The concept of nickel provinces would also tend to preclude local sulphurization of the komatiite magma to provide nickel sulphides and would instead suggest that S was added to the magma at depth and that a common magma chamber supplied the komatiites for each province or chemically distinct area.

Komatiite magmas which were generated successively with time such as Sequence 3 and 6 komatiites of Gemuts and Theron (1975) in the Kalgoorlie-Norseman Nickel Province, were chemically different. The younger group of komatiites contained less Mg and Ni and higher Cr. They are predominantly represented by thin units but the few thick units present as at Yilmia and Airport are all low Ni and high Cr varieties.

It was shown in Chapter 6 that komatiites from the Southern Cross and Forrestania sections of the Southern-Forrestania greenstone belt are quite distinct chemically. Forrestania komatiites contain relatively low Cr and Fe whereas Southern Cross komatiites are high in Cr and Fe, with Cr values of up to 2%. Although there are exceptions the Southern Cross komatiites also tend to have Ni/Mg ratios with values as low as 50.

8.5 COMMENTS ON INDIVIDUAL AREAS

Most areas appear to have been correctly categorized for the discriminant analysis but exceptions are Area A, Yerilla and Heather Well. Area A in particular exhibits strong mineralization characteristics and warrants further exploration. At Heather Well, on the basis of chemistry it was concluded that the drill holes sampled had tested the upper and not the lower part of the komatiite sequence.

At Windarra South, a metamorphosed komatiite sequence, it was shown that the komatiites actually formed three populations based on chemistry. The stratigraphically lowermost group of komatiites are now considered to be mineralized thick units. Between 1 and 4 thick units are present with the following average chemical values: NiP, 1756 ppm; Ni, 2737 ppm; Al 1.3%; Mg 17.7% and Cr 1576 ppm. The upper two groups of komatiites are thin units. Throughout the whole sequence at Windarra South NiP, Ni, CuP, Cu, Mg and CoP increase towards the base of the sequence whereas Al, Cr, Mn and Fe decrease. Zn is relatively rich in the Windarra South komatiites and averages more than 100 ppm. Mg tends to be lower at 17.7% than in equivalent thick units in the Kalgoorlie-Norseman nickel province.

At Trough Wells the relatively low percentage of samples correctly classified as Mineralized was caused by inclusion in the sample population of a large number of samples from thin unit komatiites. At Trough Wells, which is a sequence of relatively unmetamorphosed volcanic komatiites, it proved impossible to correlate individual komatiites between holes 122 m apart. Thick units predominate in the upper part of the sequence and Ni and Mg decrease towards the supposed base of the sequence which suggests that the "base" may be the stratigraphic top.

At Queen Victoria Rocks a sequence of intrusive suite komatiites, disseminated nickel and iron sulphides occur in zones within the komatiite sequence. Queen Victoria Rocks is an excellent example of a single population and shows typical mineralized intrusive suite characteristics. The nickel sulphides are primary and not related to serpentinization because serpentinization has effected less than 20% of the olivine in the komatiites.

Forrestania hole 4 intersected two very different komatiites. The main komatiite has typical mineralized intrusive characteristics but the second unit, which is separated from the main komatiite by mafic rocks shows Barren characteristics. In the second unit Ni ranges from 800 to 1500 ppm; Cr from 2000 to 5000 ppm and Ni$\underline{P}$ from 500 to 1000 ppm.

8.6 SIGNIFICANCE OF SULPHUR

Much has been written of the importance of sulphur saturation of a komatiite magma in exploration for and in the formation of nickel deposits (Naldrett 1973; Chamberlain 1968; Cameron et al. 1970; Hausen et al. 1972; Naldrett and Arndt 1976). Naldrett and Cabri (1976) concluded that the komatiites were rich in juvenile, mantle derived sulphur and contained immiscible sulphides before emplacement. The concept of nickel provinces outlined for the Yilgarn Block and the regional differences in sulphur content of Yilgarn komatiites support this conclusion. For example, at Forrestania it is apparent that the komatiite magma was rich in sulphur over a strike length of 20 km and perhaps many times that distance. The same is true for the Mt. Keith-Perseverance section of the Wiluna-Leonora Province. It seems probable that the komatiite magma for the intrusive suite in this province was derived from a common source which in turn was a different source to that of the volcanic association komatiites at Yakabindie (Turner and Randford 1975). Chamberlain (1968) states that the mean S content of ultramafic rocks is 2000 ppm. High S ultramafics as a prerequisite for mineralization was suggested by Wilson et al. (1969) in their description of the Katiniq Sill and McWalters deposit in Canada (mean 0.5% to 1% S). Hausen et al. (1972), in a study of several Western Australia and Canadian komatiite associated nickel deposits, came to the conclusion that favorable (for nickel sulphide accumulation) serpentinites had S/Ni ratios of 1:1 or more and imply that less than 2000 ppm S is unfavorable. The results of the present study indicate that average sulphur contents assumed by previous authors for ultramafic rocks (of the komatiite suite anyway) are too high, or alternatively, that Canadian komatiites contain more sulphur than West Australian komatiites. The average

sulphur value for komatiites analyzed in this study was approximately 800 ppm. The olivine cumulate sections of mineralized komatiite hosts averaged 1200 ppm whereas the silicate liquid part of the same komatiites probably averaged less than 500 ppm. The difference in mean values of sulphur between mineralized and barren komatiites is not a reliable criteria for favorability because of the wide range of sulphur values in barren komatiites. It cannot be emphasized too strongly that some samples of komatiite ore hosts, and within 20 m of sulphide accumulations, contained as little as 100 ppm S and the normal range of values was 500 to 3000 ppm. In addition, widths of barren komatiite contained up to 0.5% S over 20 m with maximum values of 2%.

Many authors have concluded that the main criteria for the formation of concentrations of magmatic sulphides are: that the host magma should be saturated in sulphur; that immiscible sulphide droplets should separate from the magma; and that the droplets are concentrated by a gravitational mechanism. Gravitational settling of sulphide droplets in place was originally favored. Naldrett (1973), however, pointed out that the droplets must have been formed before emplacement, otherwise rapid crystallization would have trapped the droplets before they could sink to the base of the flow. In mineralized volcanic suites the units which are richest in sulphur are the basal thick units and the abundance of sulphur decreases rapidly towards the top of the pile. This is illustrated by an increase in the ratios for both Ni/NiP and Co/CoP. Naldrett (1973) suggested that the sulphur content of the spinifex zone (silicate liquid) of a komatiite could represent the original sulphur content of the magma, and if high, would indicate that the komatiite was favorable to host nickel sulphides. However, within individual thick units, sulphur is relatively enriched in the olivine cumulate

section and depleted in the silicate liquid fraction, often by a factor of up to 10. Thus, when intruded the silicate liquid contained very little sulphide and apparently the sulphides in the olivine cumulate section of the komatiite are contained within the olivine crystal structure (c.f. also Hancock et al. 1973). The olivine "soaked up" residual sulphide nickel that was available during crystallization, indicating that the separation and concentration of sulphide droplets from the silicate melt was completed before olivine crystallization commenced and before emplacement or extrusion of the komatiite.

8.7 GENETIC ASPECTS

Recent work by most authors (Nesbitt 1971, Hancock et al. 1971, Ewers and Hudson 1972, Naldrett 1973, Ross and Hopkins 1975, Barrett et al. 1977) favored a magmatic origin for komatiite associated nickel sulphides at least for initial sulphide generation. An immiscible sulphide-oxide melt separates at some stage in the komatiite magma history and the resultant sulphides are concentrated and emplaced by means which are still subject to considerable debate. Barrett et al. (1976) pointed out that previous writers have neglected to consider the effects on sulphide assemblages of possible metamorphic adjustment. They suggest that at least the massive sulphide component in volcanic type deposits is a metamorphic concentration. Other origins have been proposed. Prider (1970) suggested a sulphurization hypothesis involving copper and nickel derived from ultramafic magmas and sulphide sulphur from chemical sediments. A sedimentary replacement origin has some points in its favor. Ewers (1971), Hudson (1973) and Lusk (1976) recently suggested a submarine volcanic-exhalative origin involving hydrothermal fluids followed by burial beneath a komatiite lava pile.

Local derivation of sulphide sulphur is implied where sulphide sediments are reported as being in equivalent stratigraphic positions to nickel sulphides but are absent in the vicinity of the nickel deposits. It would perhaps not be unreasonable to assume either local sulphurization of the magma or replacement of the sulphide sediment. Dalgarno (1975) stated that at Wannaway the nickel content of sulphide sediments increase as the ore zone is approached.

At Marvel Lock A the sulphide sediment adjacent to the komatiite contains 1200 ppm Ni for 7 m below the contact. At Windarra, sulphide sediments at the contact of the main komatiite contain sufficient nickel to be

classified as ore. However, as was pointed out by Hudson (1973), if local sulphide sediments were the source of sulphur and the komatiite the source of nickel, any nickel sulphide deposit should be surrounded by a large nickel depletion halo. Evidence of such halos is usually lacking. Hudson (1973) also points out that if local sulphurization of the magma is assumed, no suitable mechanism appears to exist to concentrate the dispersed nickel iron sulphide particles.

The present geochemical study, which suggests that a magma associated with nickel sulphide deposits has a slightly different chemical composition compared to a magma not associated with nickel deposits, supports the concept of a magmatic origin for nickel sulphide deposits. It does not preclude the concept of sulphurization and suggests that primary sulphurization of komatiitic magma did occur on a very large scale, probably deep in the crust, but relatively remote from the point of intrusion or extrusion. Most authors to date (Hudson 1972, Cameron et al. 1971, Wilson et Al. 1969) seem to imply that high sulphur bearing magmas were generated on a more local scale. Sulphides will separate from a crystallizing silicate melt when certain minimum sulphide sulphur concentrations are reached (Hudson 1972). Cameron et al. (1971) stated that sulphide separation is also dependent on the relative amounts of metals which are available to enter the sulphide fraction on the other components in the silicate melt and on the temperature and pressure. Wager et al. (1957) in a study of the Skaergaard intrusion, estimated that copper rich sulphides separated when the sulphur content of the magma ranged between 100 and 300 ppm. Iron sulphide separated when the silicate liquid contained 600 ppm S. Skinner and Peck (1969) reported that sulphides separated from a basaltic magma when that magma contained 380 ppm S at a

temperature of 1065°C. Very little has been published on the minimum sulphur contents of komatiite magmas required for the formation of nickel sulphides. Hudson (1972) speculated that the parent magma composition was as follows: MgO - 18% to 25%; CaO - 5% to 10%; Al_2O_3 - 7% to 20%; FeO - 8% to 12%; Ni - 1000 ppm; Cu - 100 ppm and Co - 100 ppm. Hudson also suggested that the original sulphur content was of the order of 0.58% based mainly on data from Wilson et al. (1969). Other writers such as Cameron et al. (1971) and Hausen et al. (1972) do not quote figures but imply that a minimum sulphur content of approximately 0.3% to 0.5% is required for the segregation of significant amounts of nickel sulphides. The writer considers that a komatiite parent magma composition, based on the present study and allowing for the fact that high Mg basalts were generally not included, would be of the order of MgO - 26%; CaO - 5%; Al_2O_3 - 5%; FeO - 9%; Ni - 1400 ppm; Cu - 40 ppm; Zn - 80 ppm; Cr - 2500 ppm; Mn - 1200 ppm; and Co - 115 ppm. The mean sulphur content of a parent komatiite magma from which nickel sulphides separated was probably only of the order of or less than 1000 ppm. It is possible that the sulphur was not distributed evenly and that certain parts of the magma were higher in sulphur but it seems unlikely that a sulphur content greater than 0.25% was necessary to produce significant quantities of sulphides.

Hudson (1972), Cameron et al. (1971) and Naldrett (1973) all emphasized that for nickel sulphide concentrations to form, an immiscible sulphide liquid must separate at an early stage in the crystallization of the silicate liquid to avoid the entrapment of sulphides between silicate crystals (as at Mt. Keith). It has already been shown that sulphur contents in mineralized thick units from volcanic suites vary from 0.07% to 0.20% in the cumulate portion to less than 0.05%, and in some cases as low a 0.01% in the upper silicate liquid

part. It seems justified to assume that the silicate liquid which forms 10 to 30% of the olivine cumulate portion would contain a similar sulphur content to the former silicate liquid part of the unit. Thus the sulphides in the olivine cumulates are probably held as minute blebs within the olivine crystals. It also seems probable that any immiscible sulphides separated and concentrated before substantial olivine crystallization occurred.

Groves et al. (1977) suggested that chromium is present in the sulphide oxide immiscible liquid and that ferrochromites present in sulphide deposits crystallized directly from this liquid - as a chalcophile phase. It is tempting to suggest that the difference in chromium contents between mineralized and barren ultramafics can be explained by such a mechanism.

If a sulphide oxide liquid does not form in a komatiite magma chamber, the chromium remained in the silicate liquid and crystallized mainly as chromite. Groves et al. (1977) report that chromite is absent in the ultramafic host at Nepean where most Cr is contained in chlorite, and at Wannaway. They also found that chromites present in mineralized ultramafics are rich in Zn compared to Barren ultramafics. This may explain the apparent dependence of the canonical function on relatively small changes in Zn content. Chromite is present in most nickel sulphide concentrations but little data is available on the mean chromium values of ores. At Perseverance, chrome spinel is concentrated in massive sulphide and is absent in the low grade envelope (Martin and Allchurch 1975). At Lunnon Shoot, Cr is concentrated at the base of the disseminated sulphide zone. However, concentrations in all cases are minimal (values of up to 2500 ppm Cr) and not nearly sufficient to explain the apparent removal of approximately 1000 ppm from the whole of the olivine cumulate section in each mineralized komatiite.

The physical segregation and concentration of an immiscible sulphide-oxide melt took place in some deep seated magma chamber. Sulphides did not originate from the host komatiite with which they are now associated. If segregation occurred substantially before crystallization, concentration of a sulphide oxide liquid could occur (most volcanic association deposits). However, if segregation occurred contemporaneously with olivine crystallization, perhaps because of a lower magma sulphur content, concentration did not take place. Mt. Keith is an example of the latter category. Ross and Hopkins (1975) also concluded that a sulphide melt separated prior to emplacement and discount the possibility of a simple single phase model for the development of sulphide concentrations. They advocate a complex intrusive origin incorporating pulses of sulphide melt and ultramafic magma. They also suggest that viscosity differences could result in segregation during vertical flow to yield a frontal section of sulphide melt and an olivine rich distal section. The clear contacts between massive and disseminated sulphides and the komatiite host are thus explained by assuming earlier crystallization of massive sulphides and disseminated sulphides, over which the komatiite host would continue to flow. Viscous flow was probably also important in separating olivine cumulate and silicate liquid parts of the komatiite host and it is unlikely that this differentiation took place after the magma had ceased to flow.

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APPENDIX A

GEOLOGY AND GEOCHEMISTRY OF KALGOORLIE-NORSEMAN NICKEL PROVINCE

The Kalgoorlie-Norseman Nickel Province extends from Scotia in the north to the Pioneer area in the south. The western boundary of the Wiluna-Norseman belt (Gee, 1975) forms the western boundary of the nickel province and the eastern boundary is a line which passes to the east of Kanowna and Kambalda (Fig. 2). Nickel sulphides were first discovered in Western Australia within this province at Kambalda. Since that discovery in 1966, a further seven areas with substantial nickel sulphide mineralization have been defined (now being mined or will probably be mined in the future). In addition, perhaps as many as 60 significant nickel sulphide prospects have been located and explored. The Kambalda area is the most intensely mineralized part of the province and can be regarded as the center of the province with mineralization decreasing in abundance to both north and south. It is still the only area of major economic importance. Most nickel sulphide accumulations range in size from a few thousand tonnes to several million tonnes. Individual bodies of greater than three million tonnes are relatively rare, but commonly a number of bodies occur in the same locality and collectively they may be economically viable. Mineralization in the Kalgoorlie-Norseman Nickel Province is associated with volcanic komatiite suites and has relatively low Ni to Cu ratios whereas in the Leonora-Wiluna and Forrestania Provinces the intrusive suite dominates and Ni to Cu ratios are high. The province is similar to the Windarra Nickel Province except for the association of nickel sulphides with banded iron formations, and the general lower tenor of nickel mineralization in the Windarra Province. The

main nickel sulphide areas are: Kambalda St. Ives trend, Nepean, Scotia, Spargoville, Mt. Edwards-Widgiemooltha, Wannaway and Redross. Geochemical samples for the present study were obtained from major mineralized areas at Kambalda, Nepean and Scotia; from minor mineralized areas at Bouchers, Red Dam, Mt. Jewel and Jubilee; from barren areas at Mt. Jewel North, Airport-Yilmia, Credo and Wongi North; and from one unclassified area. The geochemical results for Nepean, Scotia, Bouchers, Red Dam, Mt. Jewel, Mt. Jewel North, Credo and Wongi North will be discussed in this section. Kambalda and Airport-Yilmia were described earlier.

A.1 GEOLOGICAL SETTING

This area of the Yilgarn Block differs geologically from most other volcanic-sedimentary areas in two main aspects:

1. It can be regarded as a composite greenstone belt composed of an extremely large area of volcanic and sedimentary rocks with relatively little granitic rock within the belt itself. The volcanogenic sequence has a maximum east-west width of 160 km and north-south length of 240 km. This compares with the average greenstone belt which has a width of 30 km or less and a width to length ratio of 10 or more.
2. Magnetic, banded iron formations are relatively rare within most of the volcanogenic sequence and are restricted to the southern, eastern and western flanks of the area.

The geology of the Kalgoorlie-Norseman area was poorly understood until the late 1960's and early 1980's, but a number of recent papers, in particular papers by Williams (1970) and Gemuts and Theron (1975) have increased our knowledge considerably (Figs. 58 and 59).

A.1.1 Stratigraphy

Williams (1970) proposed multi-cycling of lithological associations for the area to the east of Kalgoorlie. In particular he recognized two lithological associations:

1. Mafic-ultramafic-volcanic;
2. Acid volcanic-volcanoclastic-clastic

and established three mafic to felsic cycles. Williams (1970) defined five associations as formations, three mafic-ultramafic and two volcanic-clastic. Gemuts and Theron (1975) for the Coolgardie-Norseman area, proposed eight associations or sequences. These sequences can be grouped into three mafic to felsic cycles and correlated with Williams' (1970) subdivisions.

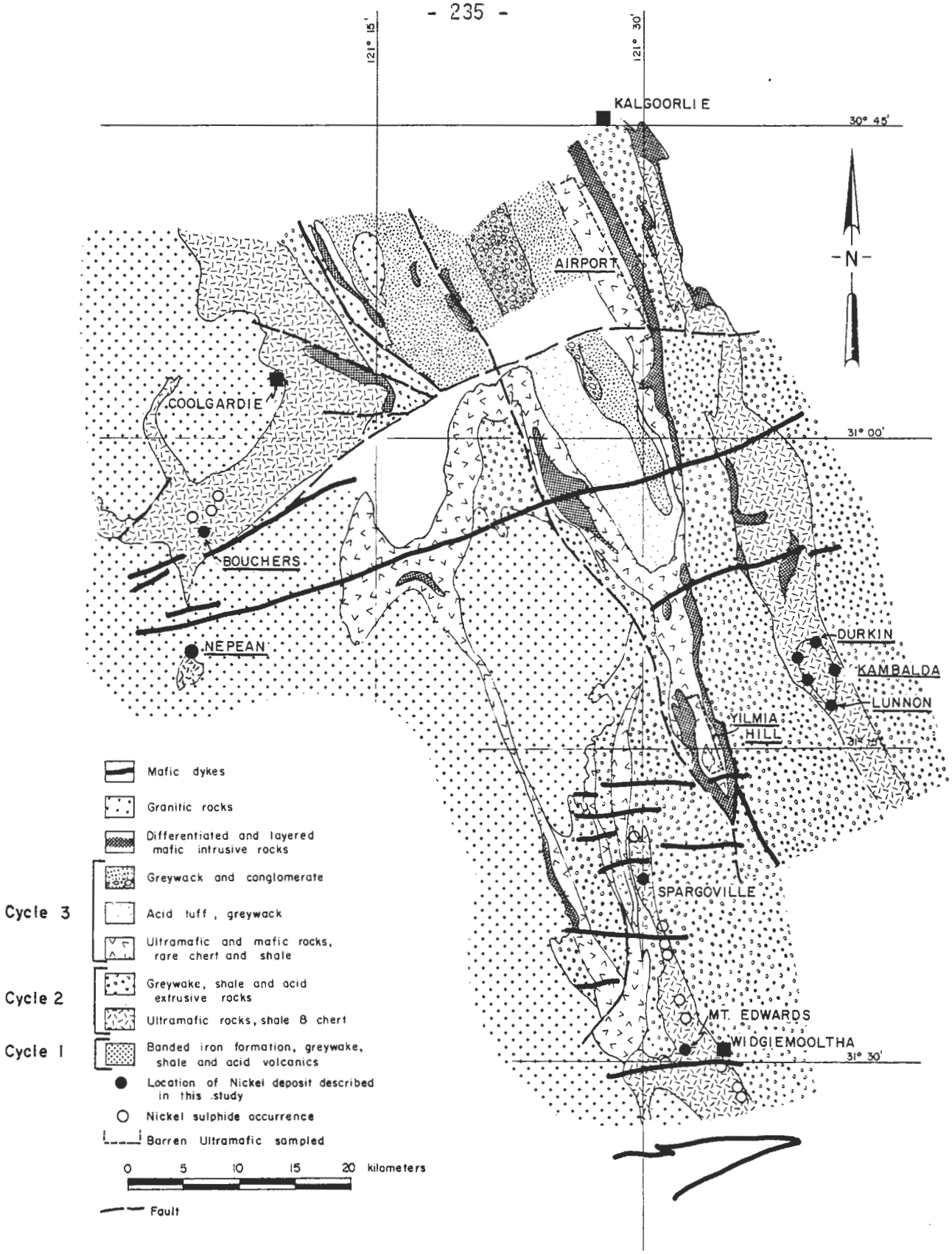

Fig. 58. Geology of the central part of the Kalgoorlie-Norseman Nickel Province (modified after Gemuts and Theron, 1975) showing location of main nickel sulphide deposits and areas sampled (Kambalda, Bouchers, Nepean, Yilmia and Airport).

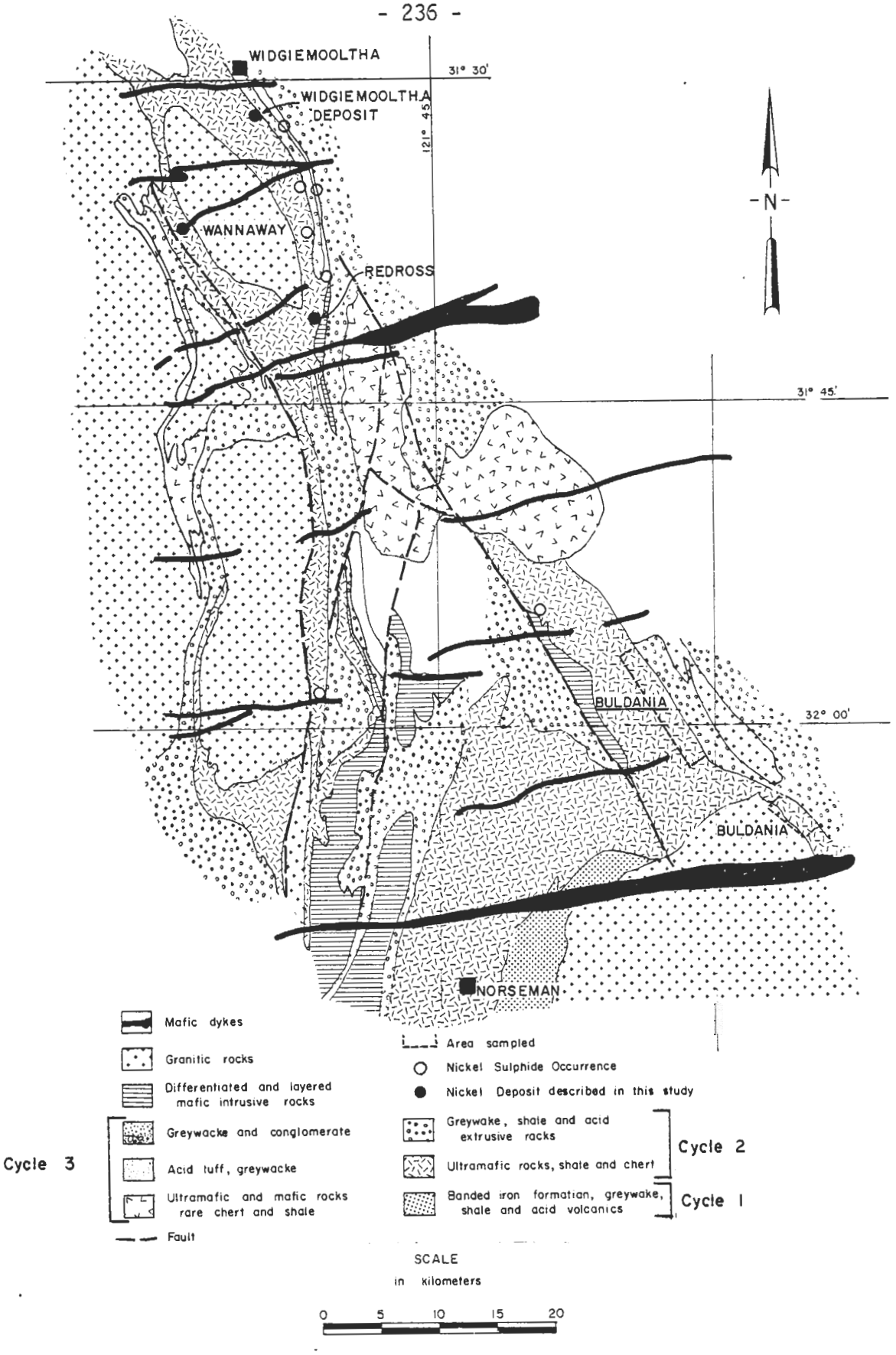

Fig. 59. Geology of southern part of Kalgoorlie-Norseman Nickel Province (modified after Gemuts and Theron, 1975), showing location of main nickel sulphide deposits and area sampled at Buldania.

1. The lowermost formation is the Morelands Formation (Williams, 1970) which, in its type area north of Kanowna, is a mafic association approximately 6,000 m in thickness. The mafic rocks are mainly lavas intercalated with minor ultramafic rocks and sediments. Gemuts and Theron (1975) correlate the Morelands Formation with the lower part of the Penneshaw Beds (Hall and Bekker, 1965) east of Norseman. Near Norseman this unit contains less mafic material and more sediments than in the type area of the Morelands Formation east of Kalgoorlie.

2. Overlying the Morelands Formation is the Gindalbie Formation which Williams (1970) described as a predominantly acid volcanic sequence 8,000 m thick. The acid volcanics consist of acid lavas interbedded with tuffs and agglomerate, rhyolite breccias, welded tuffs and, in some areas, amygdaloidal and vesicular intermediate rocks. Thick widespread deposits of oligomictic conglomerates frequently lie marginal to the acid complexes. Clastic sequences consisting of interbedded siltstone, sandstone and conglomerates with interbedded banded cherts are also present and apparently formed contemporaneously with the acid volcanic centers. Banded iron formation, probably equivalent to the banded cherts, occurs in the northeast sector of the Kurnalpi map sheet. Gemuts and Theron (1975) correlate this formation with the Noganyer Group and the upper part of the Penneshaw Beds of Hall and Bekker (1965) at Norseman. The Noganyer Group is a sedimentary sequence, overlying acid lithic tuffs and contains several well defined beds of banded iron formation.

The Morelands Formation and Gindaldie Formation are together equivalent to Sequences 1 and 2 of Gemuts and Theron (1975) and form Volcanic Cycle 1 of Williams (1970). These formations are not known to contain nickel sulphide deposits.

3. Cycle 2 commences with the Mulgabbie Formation (Williams, 1970) which is essentially a mafic association characterized by abundant rocks of the komatiite suite. According to Gemuts and Theron (1975), this formation (Sequence 3) varies from a monotonous sequence of 11,000 m of tholeiitic basalt north of Norseman to a cyclic sequence with up to three alternations of tholeiitic basalts and komatiites. The Golden Mile at Kalgoorlie falls within this formation.

Numerous thin, black, pyritic and graphitic shales and chert units occur throughout the sequence. These sulphide rich and tuffaceous units represent time breaks between mafic and ultramafic lava flows and suggest a quiescent, marine environment. According to Gemuts and Theron (1975), the top of Sequence 3 is marked by a sulphide rich "black chert marker" which consists of jarosite-stained framboidal chert and black shale.

The ultramafic rocks are predominantly extrusive komatiites and range in composition from dunite to high Mg basalt. This formation contains all the known nickel sulphide occurrences which occur in komatiite ultramafic rocks with the exception of the Jubilee prospect and other minor sulphide occurrences in the Kalpini Formation.

4. Overlying the Mulgabbie Formation is a sequence of acid volcanic rocks which are in turn overlain by a thick, turbidite clastic sequence. The entire sequence has been named the Gundocherta Formation by Williams (1970); the lower part of the sequence is named the Black Flag Beds in the Kalgoorlie area (Woodall, 1965); and Gemuts and Theron (1975) divide it into two units named Sequence 4 and Sequence 5. The acid volcanic rocks are in many areas replaced by volcanogenic sediments such as tuff, agglomerate, greywacke, etc. and in other areas it is not uncommon for turbidite sediments to immediately overlie the Mulgabbie Formation.

5. Overlying Cycle 2 rocks is a mafic and ultramafic sequence named the Kalpini Formation by Williams (1970) and Sequence 6 by Gemuts and Theron (1975). This sequence forms the basal unit of Cycle 3 and consists of tholeiitic basalts, ultramafic komatiite lavas and high-Mg basalts with interlayered thin sulphide rich sediments and cherts. The sequence is best exposed in the Yilmia area south of Kalgoorlie and north of the Jubilee prospect. It is similar to the Mulgabbie Formation or Sequence 3 (Gemuts and Theron, 1975) but appears to contain less dunitic and peridotitic ultramafic rocks (but not necessarily less ultramafic rock in total). Nickel sulphide deposits are not common in this formation.

6. Cycle 3 is terminated with a sequence of acid volcanic and sedimentary rocks consisting of feldspathic greywacke, tuff, quartz-feldspar porphyry, rhyolite flows and volcanic conglomerates and breccias. Gemuts and Theron (1975) refer to this unit as Sequence 7.

7. The youngest unit in the Kalgoorlie-Norseman belt is a thick unit of arenaceous sandstone, greywacke and conglomerate. It is known as the Kurrawang Conglomerate. Gemuts and Theron (1975) appear to correlate Sequence 6, 7 and 8 with the Kalpini Formation but it is probable that the Kalpini Formation is equivalent only with Sequence 6.

A.1.2 Structure

Regional structure tends to be complex and has proved difficult to unravel. Strike-slip faults are common and are often undetected in areas of poor outcrop and uncertain stratigraphy. Anticlines are sheared or faulted out and individual fault blocks may be moved tens of kilometers. There is a tendency to simplify structure but areas which have been studied in detail such as the Golden Mile (Travis et al. 1971) indicate that such an approach is misleading.

Two main periods of folding have produced predominantly north-northeast folds with superimposed east-west crossfolds. The east-west crossfolds appear to be related to synchronous intrusion of granite in anticlinal crests. The north-northeast trend is accentuated by numerous strike-slip faults.

A.1.3 Intrusive Rocks

Intrusive rocks include large differentiated and layered mafic bodies, porphyry dykes, linear east-west norite dykes and granites.

The mafic intrusives are thick coarse-grained gabbroic sills which, according to Gemuts and Theron (1975) are intruded near the boundaries of Sequences 3 and 4 and within Sequence 6. Some of these bodies are host rocks for gold mineralization. The layered mafic bodies often grade from serpentinized dunite and harzburgite at the base through norite and gabbro to granophyric gabbros at the top.

East-west mafic dykes are a characteristic of the Yilgarn Block outside the Southwest Province. They range up to 3.2 km in width and may extend along strike for hundreds of kilometers (Figs. 58 and 59). The dykes vary in composition from picritic through pyroxenitic to titanium and iron enriched tholeiitic types.

Granitic rocks have intruded the cores of many anticlines and modify structures locally in many areas. They are usually potassium rich, range from medium to coarse-grained and are commonly porphyritic with microcline phenocrysts (Gemuts and Theron, 1975). The granitic rocks which border the belt to the west are little known but include both intrusive and gneissic granites.

A.2 WIDGIEMOOLTHA DOME - SPARGOVILLE NICKEL OCCURRENCES

This area includes most of the southwest flank of the Kalgoorlie Norseman Province and contains significant nickel sulphide deposits at Spargoville, Mt. Edwards, Widgiemooltha, Wannaway and Redross. No samples were obtained from these occurrences but for completeness they are briefly described below.

A.2.1 Spargoville

The Spargoville area contains four separate nickel sulphide occurrences (Fig. 60) and is situated 65 km south of Kalgoorlie (Fig. 58). All occurrences are small and published ore reserves for two of the deposits are 120,000 tonnes and 715,000 tonnes at 2.32% Ni and 2.47% Ni respectively (Andrews, 1975). Three ultramafic sequences are present but nickel sulphides are restricted to the eastern sequence (Fig. 60). According to Gemuts and Theron (1975) the eastern ultramafics are part of Sequence 3 or the Mulgabbie Formation and the western ultramafics are a part of Sequence 6. Gemuts and Theron (1975) separate the sequences with a major fault. The mineralized belt of ultramafics consist of at least three separate bodies with an overall strike length of 10 km. Individual bodies seldom exceed 100 m in width and consist predominantly of tremolite chlorite rock with discontinuous dunite lenses near the basal ultramafic contact.

Hancock et al. (1971) described in detail the petrology, chemistry and alteration through the lowermost dunite lens shown in Fig. 61. They showed that the original rock consisted of forsterite (91% to 93% Fe) with minor ilmenite and iron, nickel and copper sulphides. Magnesium was constant throughout except towards the lower contact due to diluting effects of sulphides; sulphur showed a steady increase with depth and an abrupt increase

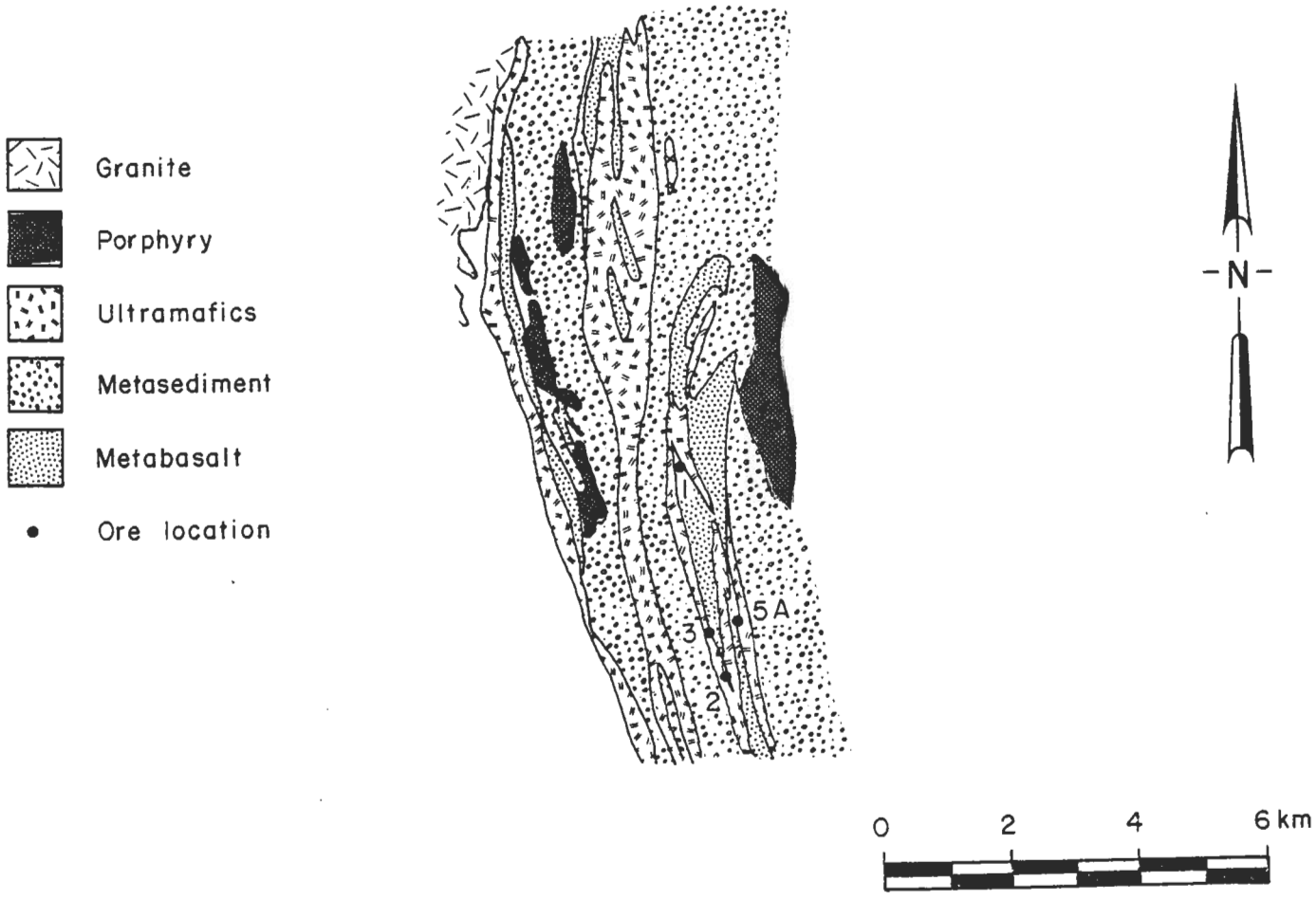

Fig. 60. Geological plan of the Spargoville area (after Andrews, 1975).

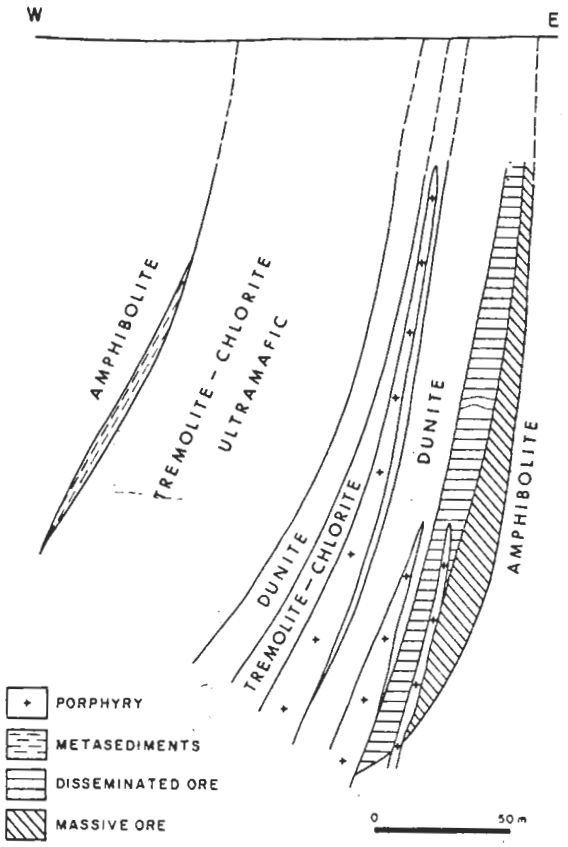

Fig. 61. Section through nickel sulphide body at Spargoville (after Hancock et al., 1971).

0.6 m above the contact; nickel showed a steady increase with depth. Copper was present in trace amounts only in the uppermost one-third and increased to significant but unspecified levels in the lower one-third of the dunite. Two whole rock analyses are shown in Table 32. Note the low value for chromium (0.15%) in sample 4. The sulphur values of 0.56 and 1.31% are extremely high for ultramafic rock some distance from significant mineralization. The footwall and hangingwall rocks consist of pillowed mafic volcanics and metasedimentary rocks which range from impure quartzites to pyritic carbonaceous shales.

Although Hancock et al. (1971) do not mention it, interpretation of their elemental and mineral variation plots suggests that a thin tremolite rich, low magnesium zone occurs at the lower contact. This zone may represent a chilled margin. The tremolite-chlorite ultramafic in Fig. 61 contains rare, narrow dunitic zones and it is probable that this section of the ultramafic sequence consists of multiple thin ultramafic flows. In addition, the tremolite-chlorite zone immediately overlying the lower dunite unit in Fig. 61 is probably part of a single thick unit in which the dunite represents the cumulate zone and the tremolite chlorite is the upper, silicate liquid low magnesium top.

The mineralization consists primarily of pyrrhotite and pentlandite with subordina te chalcopyrite and pyrite. Available data (Andrews, 1975) suggests that pyrrhotite-pentlandite ratio is approximately one and that nickel-copper ratios average 12:1. In the dunite described by Hancock et al. (1971) towards the top of the dunite sulphides occur as minute droplets within crystals of olivine and as irregular small grains interstitial to olivine. The interstitial sulphide content increases with depth.

A.2.2 Mt. Edwards

Mt. Edwards is a small to medium nickel sulphide body situated approximately 80 km south of Kalgoorlie (Fig. 58) and is the largest of seven separate bodies along a strike length of 11 km. Announced ore reserves are 1.54 million tonnes at 2.2% Ni and 0.2% Cu (Inal Staff, 1975). The mineralized komatiite unit is within the second komatiite sequence in the area and the lowermost komatiite sequence is not mineralized. The Mt. Edwards deposit consists of several sulphide lenses within two basal komatiites of a thick sequence of ultramafic flows (Fig. 62).

A narrow, lensing, graphitic, sulphide rich sediment occurs along the footwall contacts and other similar sediments occur between the two basal komatiites. Contact is made locally between massive nickel sulphides and sulphide rich sediments and where this occurs the underlying unit contains chalcopyrite with pyrrhotite-pentlandite in fracture fillings. The mineralization in the lower komatiite unit is characteristically of higher grade but is less abundant than mineralization in the overlying komatiite. Most of the ore grade mineralization is finely disseminated pyrrhotite-pentlandite-chalcopyrite in the upper unit. Nickel-copper ratio is 11:1. Representative analyses from two ultramafic units are reproduced in Table 10 from Inal Staff (1975).

A.2.3 Widgiemooltha

The Widgiemooltha prospect is 90 km south of Kalgoorlie (Fig. 58) and is one of numerous nickel sulphide occurrences around the Widgiemooltha Dome. The dome has a core of intrusive granite, 10 km by 7 km, and is flanked by a sequence of metamorphosed basaltic, ultramafic and doleritic units with interbedded fine-grained metasediments. The deposit is a small lens of nickel

	1	2	3	4	5
SiO_2	43.60	50.50	49.10	42.40	28.20
Al_2O_3	2.44	4.86	14.60	2.81	15.40
Fe	5.98	6.33	8.13	11.30(B)	9.80(B)
MgO	35.50	22.60	8.60	32.50	33.10
CaO	1.02	7.43	10.50	4.20	0.07
K_2O	0.24	0.28	0.80	0.04	0.11
TiO_2	0.13	0.25	0.72	0.17	0.53
Ni	0.25	0.16	0.01	0.39(A)	0.02(A)
MaO	ND	ND	ND	0.22	0.08
S	ND	ND	ND	0.56	1.31
H_2O	11.10	4.10	1.00	5.24	12.37
Cu(ppm)	ND	ND	ND	50	190
Co(ppm)	ND	ND	ND	120	50
Cr(ppm)	ND	ND	ND	1500	150

1. Porphyritic peridotite, Mt. Edwards (Inal Staff, 1975).
2. Tremolite rich rock, Mt. Edwards (Inal Staff, 1975).
3. Footwall metabasalt, Mt. Edwards (Inal Staff, 1975).
4. Dunite, Spargoville (Hancock et al, 1971).
5. Dunite, Spargoville near Porphyry (Hancock et al, 1971).

A - Ni as NiO
B - Fe as FeO

Table 32. Analyses of komatiites from Spargoville and Mt. Edwards (from Inal Staff, 1975 and Hancock et al., 1971).

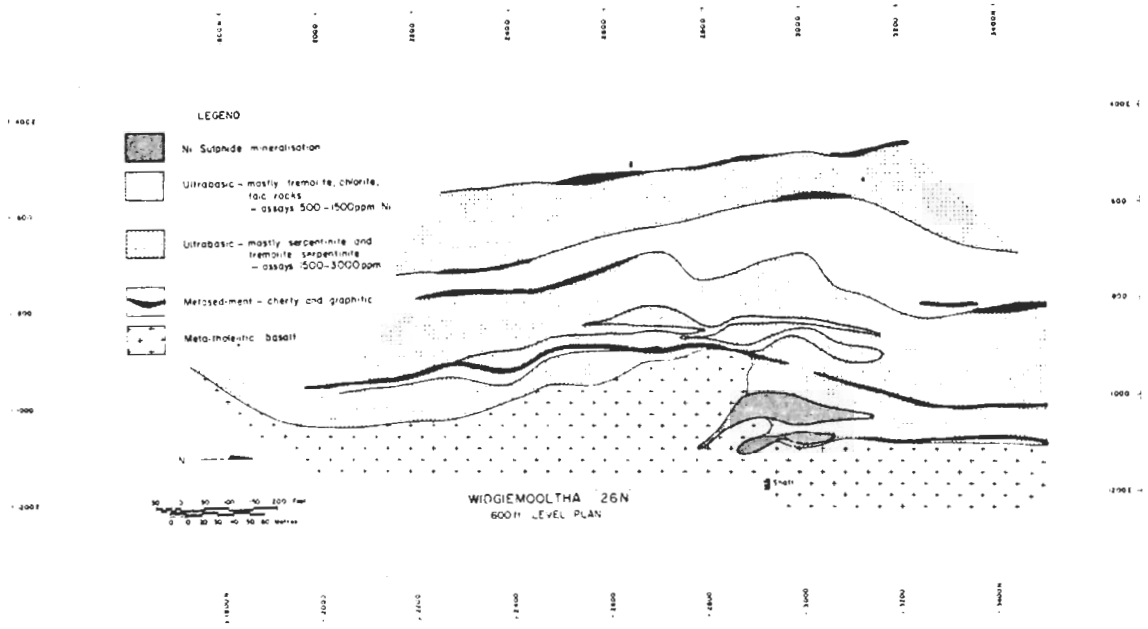

Fig. 62. Geological plan, 600 ft. level, Mt. Edwards deposit (after Inal Staff, 1975). Note the consistent stratigraphic position of metasediment bands in the komatite lava pile. The ultrabasic divisions shown are probably similar to the thick and thin units at Kambalda.

sulphides in an embayment at an ultramafic-dolerite contact (Dalgarno, 1975). The sulphides consist of a high grade, massive zone up to 1.5 m thick overlain by and within serpentinite 5 to 15 m of low grade disseminated sulphides. Ore reserves are quoted as 0.9 m tonnes at 1.23% Ni and 0.10% Cu.

A.2.4 Wannaway

Wannaway is situated on the west flank of the Widgiemooltha Dome 14 km south-southwest of Widgiemooltha (Fig. 58). It consists mainly of weakly disseminated sulphides in serpentinite, with relatively minor amounts of massive or heavily disseminated sulphides. Ore reserves are 4.5 million tonnes at 1.22% Ni and 0.10% Cu (Dalgarno, 1975). The komatiite sequence contains at least four sub-units separated by persistent sediment bands. Serpentinite after olivine peridotite and dunite form the lower third of the sequence and chlorite and tremolite rich komatiites dominate the upper two-thirds. This sequence can be interpreted as several thick unit komatiites overlain by multiple thin units which is similar to Kambalda or Windarra South. The sulphide deposit is associated with a saucer shaped embayment in the basal komatiite basalt contact. Mineralization varies up to 18 m thick. According to Dalgarno (1975), cherty sediments which occur along strike from the deposit show a progressive increase in nickel content as the mineralization zone is approached.. The disseminated sulphides contain 3% to 8% total sulphide and the pyrrhotite-pentlandite ratio may be as low as 1:9. In contrast, in the massive sulphide lenses, the ratio varies from 4:1 to 6:1. Nickel-copper ratios vary from 10:1 to 20:1 and are higher in the disseminated sulphides.

A.2.5 Redross

The Redross nickel sulphide deposit is situated 25 km south-southeast of Widgiemooltha (Fig. 58). It is a small, high grade occurrence and ore reserves are 1 million tonnes of 3.5% Ni and 0.3% Cu (Dalgarno, 1975). The mineralization occurs in a narrow (65-110 m) olivine peridotite which according to Dalgarno (1975) was intruded into dense, pillowed tholeiitic basalts. The basalts are submarine flows and have interbeds of chert, black shale and tuffaceous sediments. Mineralization occurs near the basal contact of the komatiite and associated with sediment rocks within the komatiite. It is partly shear controlled and has been remobilized as a portion of the orebody is actually within footwall metabasalts. The primary sulphides consist of pyrrhotite, pentlandite, pyrite and chalcopyrite. Massive sulphides comprise 30% of the total and contain up to 18% Ni. Nickel-copper ratio varies from 6:1 to 50:1. Dalgarno (1975) concludes that the ultramafic is a single intrusive unit which was intruded as a high level sill of peridotite or dunite. The sulphides were intruded with the ultramafic and later remobilized into structures.

A.3 GEOLOGY AND GEOCHEMISTRY OF AREAS SAMPLED

A.3.1 Bouchers

Bouchers is a minor occurrence of nickel sulphides approximately 16 km south of Coolgardie (Fig. 58). It is one of several small occurrences that are present at the base of a komatiite ultramafic sequence approximately 11 km in strike length. Twenty-seven diamond drill holes were completed by various companies in an area of 1,000 m by 400 m.

A komatiite sequence ranging from 80 to 400 m in thickness is overlain by at least 400 m of meta tholeiitic basalts and underlain by a discontinuous zone of pyritic sediments (10 m thick) and a metagabbro unit which ranges from 100 to 300 m thick. The ultramafic sequence dips vertically and hosts nickel sulphide mineralization along its eastern contact (Fig. 63).

According to Halberg et al. (1973), the basal section of part of the komatiite sequence north of Bouchers is a peridotite which is overlain by a series of chlorite tremolite rocks which in turn contain numerous zones of spinifex texture and are believed to be high-Mg basalts. Development of secondary olivines is common. No spinifex zones were noted in drill core but wide zones of spinifex-like metamorphic olivines are present. Mineralization up to 2 m thick occurs in areas of the contact where the underlying pyritic sediment is absent. Pyrrhotite and pentlandite in both disseminated and massive form are the main sulphide minerals. Figs. 63 and 64 show location of diamond drill holes sampled and the approximate extent of the mineralization.

Two hundred and seventy-four (274) core samples selected at 6.1 m intervals were obtained from nine drill holes. Holes 3 (Fig. 65), 16 (Fig. 66) and 12 (Fig. 67) did not reach the basal ultramafic contact and thus did not effectively test for nickel sulphide accumulations. The width of

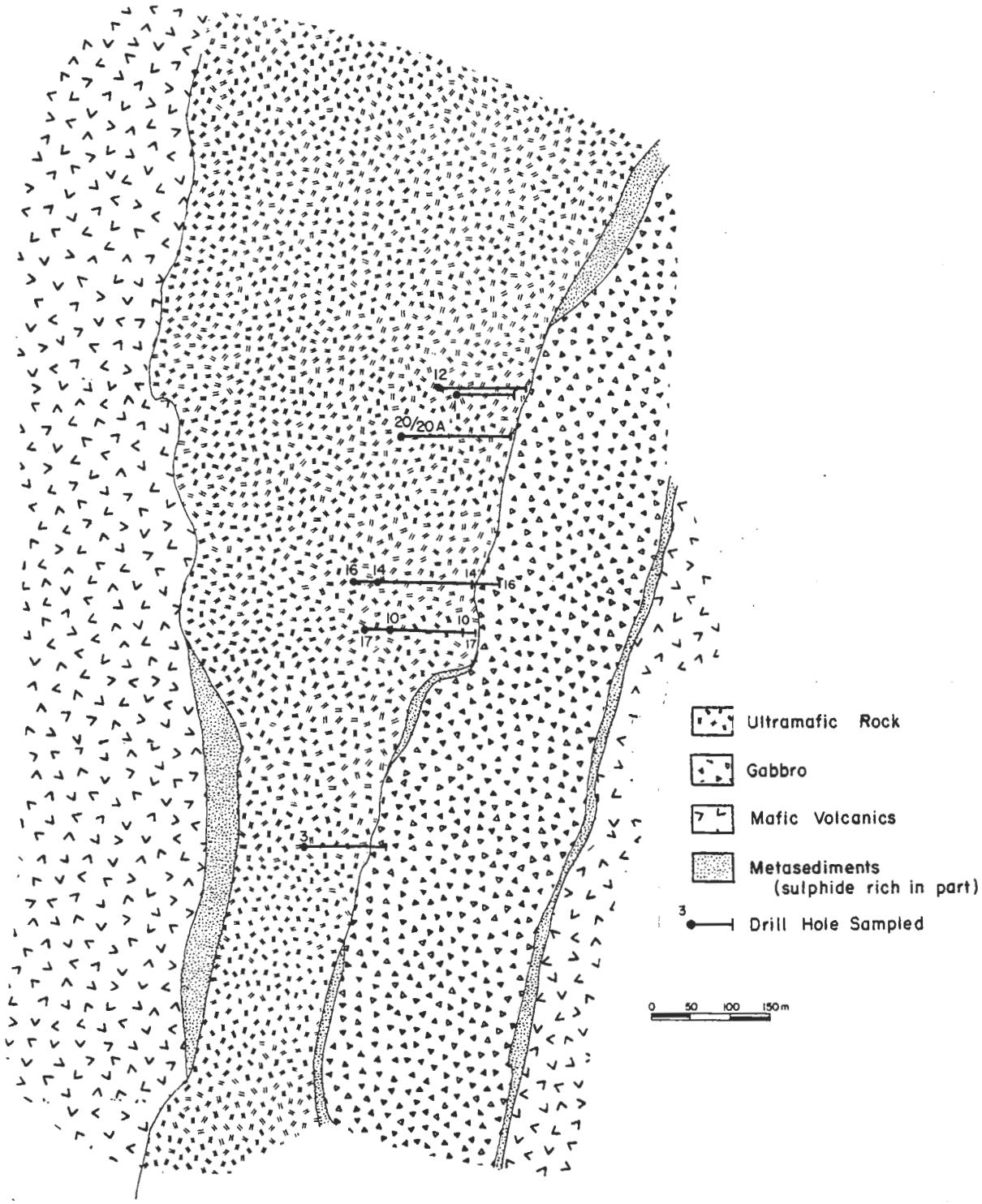

Fig. 63. Geological sketch plan of Bouchers prospect - showing location of drill holes sampled.

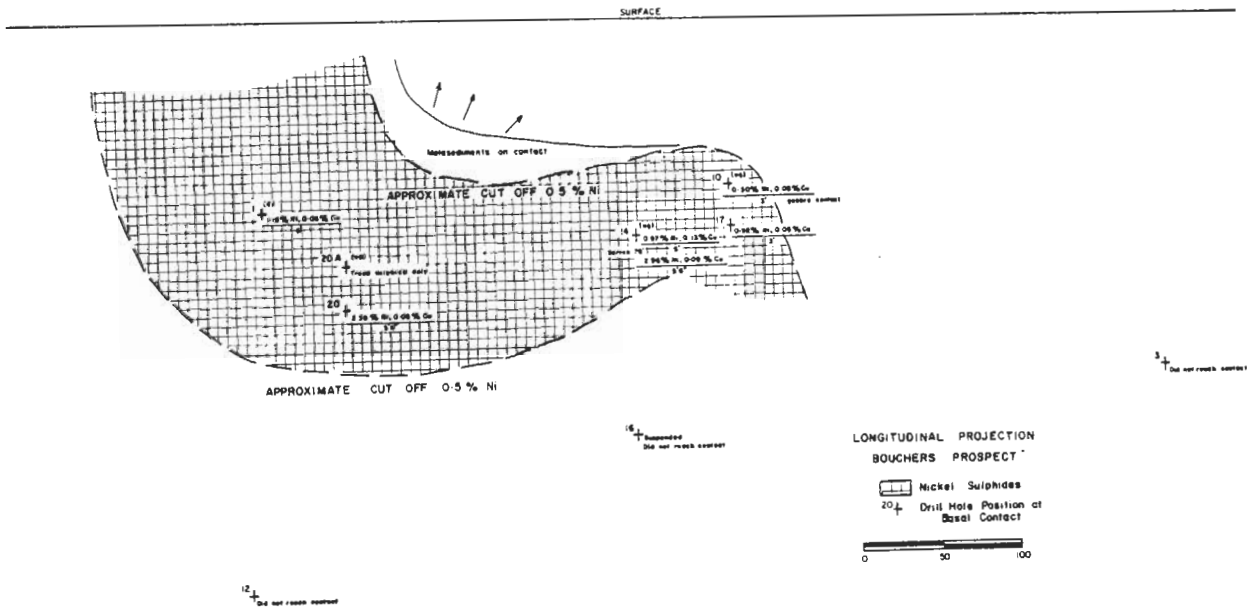

Fig. 64. Longitudinal section projected to basal komatiite contact, showing outline of nickel sulphide mineralization at Bouchers, and relative positions of holes sampled.

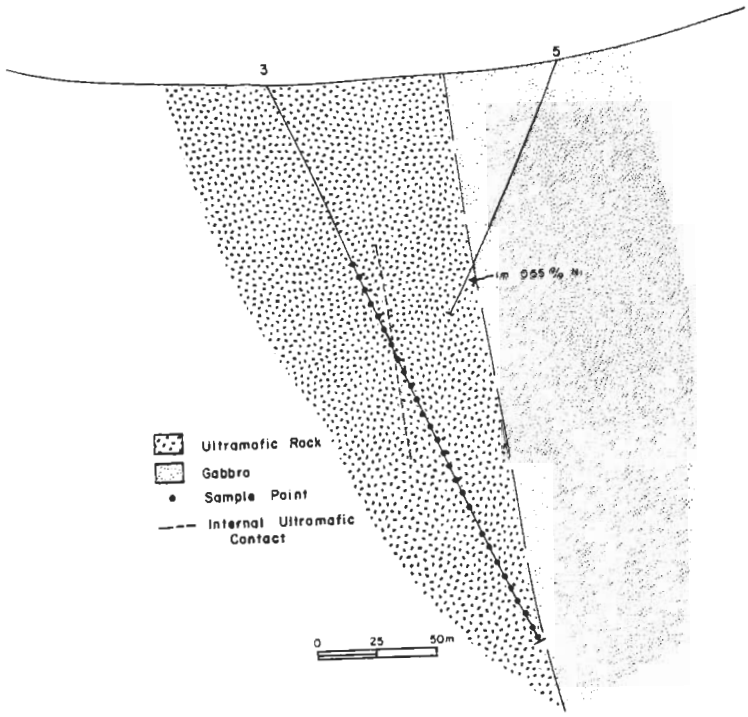

Fig. 65 . Cross section at Bouchers through holes 3 and 5 showing geology and sample points.

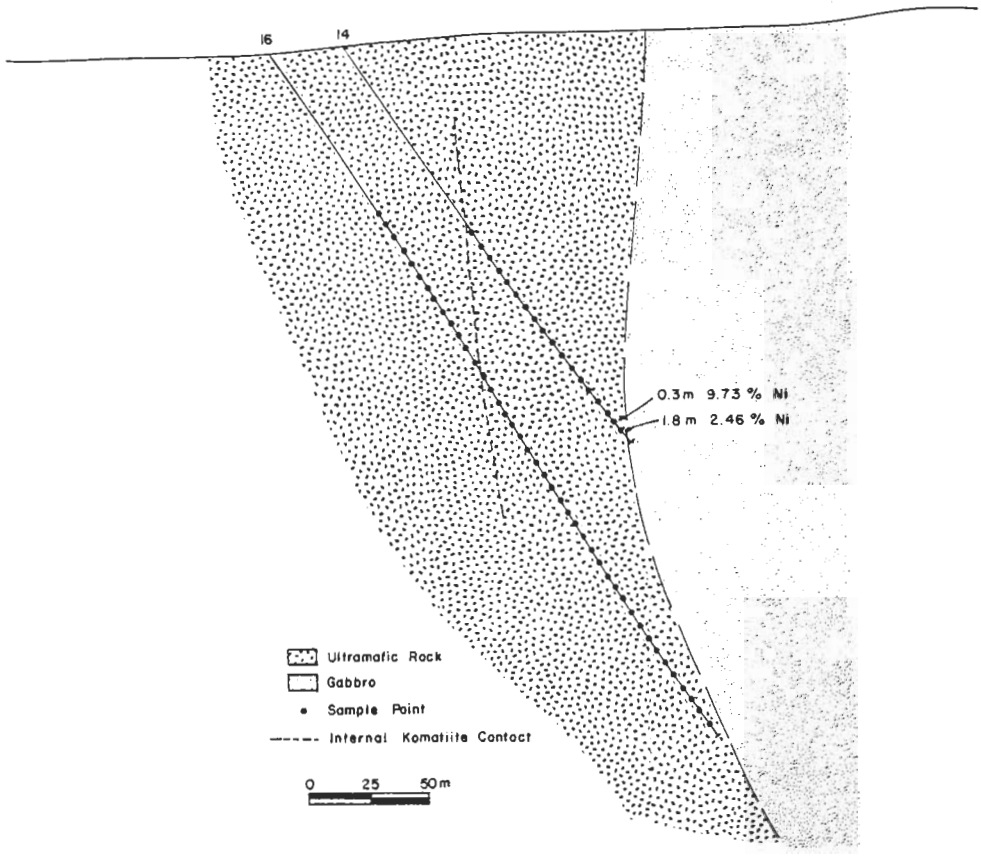

Fig. 66. Cross section at Bouchers through holes 16 and 14 showing geology and sample points.

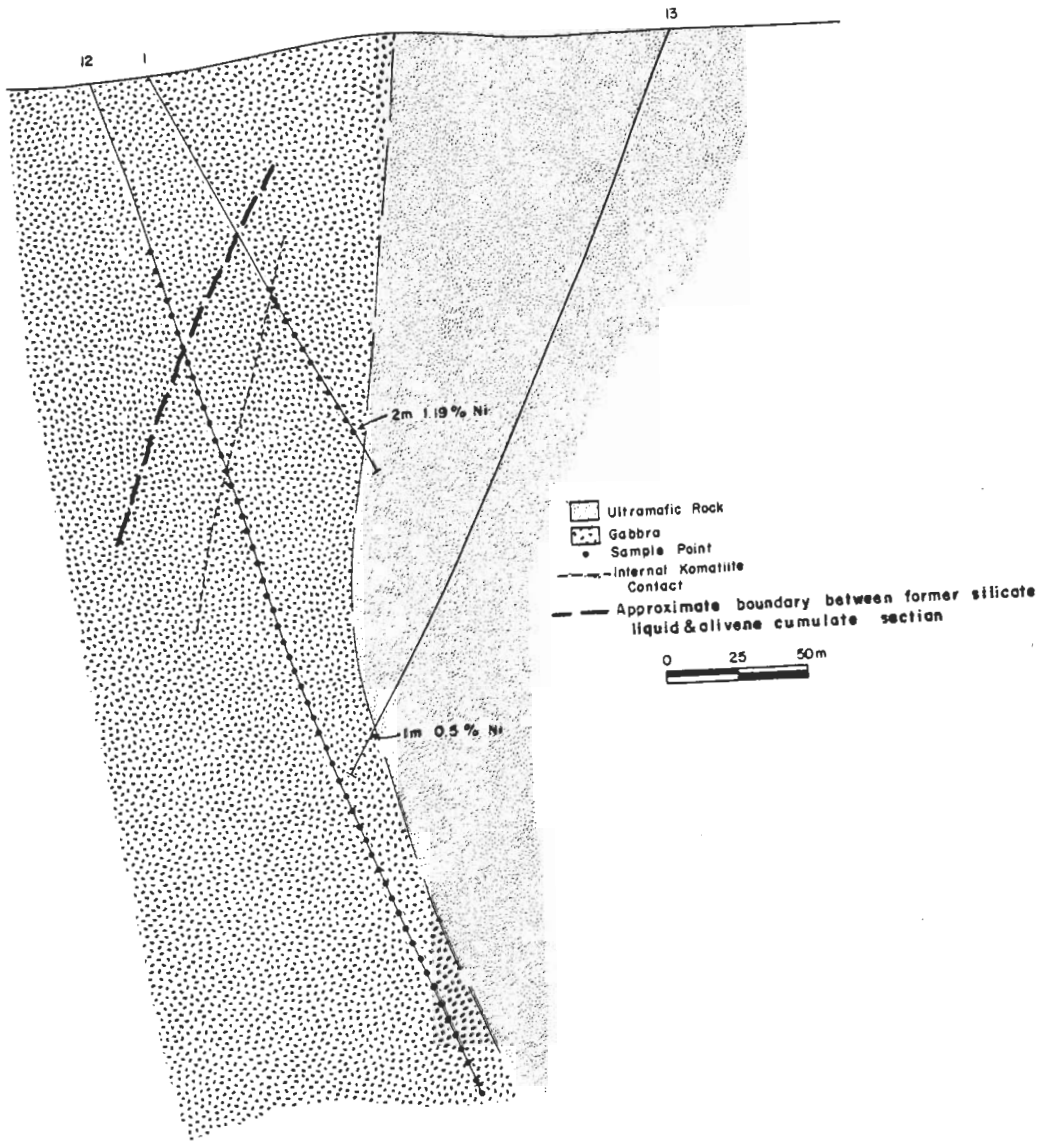

Fig. 67. Cross section at Bouchers through holes 12, 1 and 13 showing geology and sample points. The approximate division between silicate liquid and olivene cumulate parts of the basal thick unit is shown

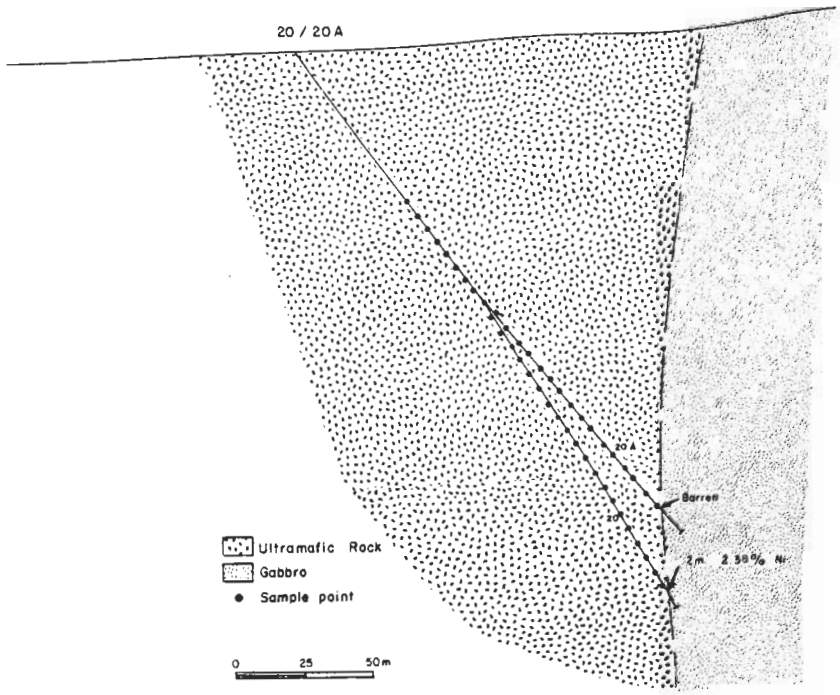

Fig. 68., Cross section at Bouchers through holes 20 and 20A showing geology and sample points.

Hole No.	Sample No.	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co
17	1	1.91	687	2800	9	10	1.00	0.12	22.40	40	1900	750	6.00	0.17	25	105
	2	2.03	487	2300	3	5	1.65	0.07	25.20	50	1950	850	5.00	0.48	28	110
	3	2.90	412	3100	2.5	5	1.10	1.05	21.40	40	2400	450	4.60	0.07	13	95
	4	2.23	1875	3200	4	5	0.95	1.05	21.40	30	1850	950	3.00	0.14	50	110
	5	1.38	1237	2700	5	5	0.65	0.03	23.20	30	1300	850	4.70	0.08	45	110
	6	0.79	1387	2425	6	8	0.45	0.02	25.20	40	900	800	4.40	0.06	50	105
	7	1.44	1400	3400	3	5	0.62	0.03	28.20	40	1450	1100	4.90	0.11	48	135
	8	1.71	762	2650	2.5	5	0.63	0.18	28.80	40	1150	1100	4.90	0.10	33	115
	9	1.29	1000	2700	3	5	0.42	0.04	28.00	40	1000	950	4.60	0.06	48	125
	10	1.52	1100	2900	5	8	0.75	0.08	28.20	50	1600	1150	5.10	0.14	40	120
	11	2.06	537	1750	2.5	5	0.80	1.30	25.80	40	950	750	5.30	0.12	38	115
	12	1.63	912	2175	33	35	0.69	1.50	25.20	40	950	750	5.80	0.18	45	120
	13	2.76	1350	3650	58	148	1.90	1.30	13.30	50	1850	500	4.00	0.32	48	130
	14	1.71	1050	2450	5	8	1.30	0.68	24.40	50	1700	1000	5.80	0.29	60	120
14	1	2.47	1725	2075	85	95	1.30	4.60	16.20	30	1400	1050	5.00	0.23	73	110
	2	1.90	1325	2725	6	10	1.15	0.34	21.60	30	1550	350	4.00	0.19	55	105
	3	1.62	887	2600	10	10	0.71	0.10	25.20	30	1350	300	4.50	0.08	60	115
	4	1.80	375	2400	4	5	1.00	0.04	25.70	40	1650	600	4.60	0.12	23	95
	5	1.07	1000	2800	4	5	0.71	0.06	24.00	40	1250	450	4.50	0.07	48	105
	6	1.65	25	50	3	5	0.59	0.89	16.20	140	100	800	3.20	0.03	5	40
	7	1.27	312	1750	3	5	0.23	0.21	28.20	50	550	950	4.80	0.04	18	100
	8	1.70	762	2475	4	5	0.74	0.48	25.70	40	1450	700	4.80	0.08	48	110
	9	1.56	1175	2525	4	5	1.00	1.05	23.00	40	1250	600	4.60	0.12	35	110
	10	1.24	900	2275	4	5	0.59	0.61	26.00	50	1000	900	4.80	0.11	35	110
	11	1.88	875	1975	4	5	0.60	2.60	21.40	30	1050	650	3.20	0.18	30	80
	12	1.68	937	2300	4	5	0.95	1.15	23.00	40	1350	800	4.50	0.14	38	100
	13	1.71	1125	2500	11	18	0.86	1.05	23.00	40	1250	950	4.60	0.11	53	105
	14	1.54	750	2400	6	10	1.00	0.24	24.20	50	1300	900	5.20	0.24	40	110
	15	1.33	775	2600	4	5	1.15	0.24	24.80	50	1350	950	5.20	0.15	40	115
	16	1.71	875	2550	33	40	1.15	0.42	25.20	50	1500	850	5.20	0.15	45	115
	17	1.67	900	2375	5	10	1.10	1.40	22.00	50	1200	750	4.80	0.15	45	110
10	1	ND	700	1650	3	5	0.85	3.10	17.30	50	1150	1150	5.30	0.12	25	105
	2	ND	850	2600	8	10	1.10	0.05	22.60	30	1650	600	5.30	0.14	13	125
	3	ND	550	2550	5	8	1.00	0.03	22.60	40	1550	450	5.10	0.14	15	105
	4	ND	550	2650	3	5	0.77	0.08	22.60	40	1550	500	4.40	0.08	15	95
	5	ND	388	2525	5	8	0.85	0.05	22.60	30	1550	400	4.80	0.10	10	80
	6	ND	538	2000	4	5	0.42	0.29	22.60	30	650	650	4.10	0.04	40	115
	7	ND	750	2300	3	5	0.61	0.10	23.30	40	1000	850	3.90	0.07	38	95
	8	ND	988	2800	3	5	0.60	0.02	25.80	40	1400	800	4.40	0.06	38	110
	9	ND	1225	3150	5	5	1.10	0.06	25.00	40	1750	900	5.10	0.12	45	125
	10	ND	1150	2800	6	8	0.92	0.28	24.00	40	1500	750	5.10	0.16	48	125
	11	ND	413	2600	2.5	5	0.83	4.70	8.70	50	1350	550	4.40	0.09	28	90
	12	ND	413	2150	2.5	15	0.92	13.30	12.00	110	1250	950	3.30	0.10	30	90
	13	ND	663	3250	2.5	5	1.30	2.00	9.70	60	2000	1300	6.60	0.16	105	195
1	1	2.24	775	2125	3	5	1.00	0.39	20.10	20	1550	250	5.40	0.12	23	80
	2	1.84	1100	2350	2.5	5	0.33	0.85	22.60	30	950	500	3.80	0.04	43	95
	3	1.64	1225	2475	2.5	5	0.42	0.11	23.00	30	1050	500	4.40	0.04	53	105
	4	1.52	988	2700	2.5	5	0.62	0.04	24.20	40	1200	550	4.10	0.06	55	115
	5	1.87	1275	3000	2.5	5	0.61	0.23	20.60	40	1500	550	4.00	0.06	53	110
	6	1.63	1175	2750	2.5	5	0.64	0.07	26.00	40	1300	500	4.40	0.07	48	120
	7	1.66	913	2400	2.5	5	1.20	0.50	25.00	40	1200	600	4.10	0.18	43	105
	8	1.94	775	2750	3	5	0.95	0.36	24.60	40	1550	600	4.10	0.13	45	115
	9	2.36	425	2250	2.5	5	0.72	0.35	25.00	40	1300	900	4.50	0.13	28	110
	10	2.41	1000	2050	23	48	1.10	4.70	18.80	40	1200	1050	4.80	0.23	50	110
	11	0.50	1075	1400	9	13	0.69	3.45	19.00	40	350	1100	5.40	0.09	60	95

Table 33. Geochemical analyses and canonical scores for samples from holes 1, 10, 14 and 17 at Bouchers. The relatively high Mg values reflect the presence of abundant metamorphic olivene and are not necessarily indicative of a dunitic parent. The relatively high Ni and low Cr values reflect a Mineralized environment.

komatiite sampled is a maximum of 100 m and three-quarters of the samples represent the basal 50 m of ultramafic. The komatiites sampled are homogeneous and the geochemical results, discriminant analysis scores and principal component scores, all indicate that the samples were derived from a relatively few thick units. Bouchers is above the arithmetic mean for mineralized ultramafics in Ni (1,980 ppm) and Mg (24.0%) only (Table 3) and substantially below the arithmetic mean for all other determinations. Compared to all komatiites studied, Bouchers is relatively high in Ni and Mg and significantly lower in Cu, Cr, Mn, Fe, Al and Ca. In general, Ni and Mg increase towards the base of the sequence; Cr, Fe and Mn tend to decrease. The higher than average Mg values do not necessarily reflect a more dunitic parent but are at least partly caused by the higher metamorphic grade which has reconstituted much of the rock to metamorphic olivine (and removed volatiles).

Metamorphism has obliterated all traces of original texture and thus petrographic study cannot separate the sequence into separate komatiite units. The geochemistry, however, is sufficiently detailed to provide a significant insight into the composition of the sequence. Holes 20 (Fig. 68 and 69), 17 (Fig. 70 Table 33), 14 (Fig. 66, Table 33), 10 (Fig. 70 Table 33) and 1 (Fig. 67, Table 33) appear to be confined to a single thick komatiite unit, whereas holes 3 (Figs. 65 and 71), 12 (Figs. 67 and 72) and 16 (Figs. 66 and 73) all intersected at least two units. In hole 3 (Fig. 71) which is south of the mineralization, the section of hole between 76 and 131 m appears to represent the basal portion of a thick unit komatiite. From 131 m to the end of the hole is a second thick differentiated komatiite with the section between 131 and 174 m representing the upper less magnesium rich section (silicate liquid section) which before metamorphism may have exhibited

Hole No.	Mean Score Discriminant Function A	Mean Score Discriminant Function B	Mean Cr	Mean Mg	Mean Ni	Mean NiP	Mean Ni/Cr	Mean Ni/NiP
20	0.51	1.89						
17	0.36	1.80						
16	0.20	n.d.	1258	27.0	2541	615	2.02	4.13
14	0.21	1.63	1297	24.0	2401	922	1.85	2.60
3	0.78	2.19	1807	18.8	1883	742	1.04	2.54
12	0.69	n.d.						
10	0.54	n.d.						
1	0.50	n.d.						

Mean score Discriminant Function A, all mineralized areas - 0.59

Mean score Discriminant Function B, all mineralized areas - 1.72

Table 34. Mean canonical scores for all holes at Bouchers, and mean geochemical values for holes 3, 14 and 16. Hole 3 is along strike from the nickel sulphide mineralization and contains higher Cr and lower Ni and Mg than other holes at Bouchers. The mean canonical score of 2.19 for hole 3 indicates a decrease in mineralization potential relative to the other holes.

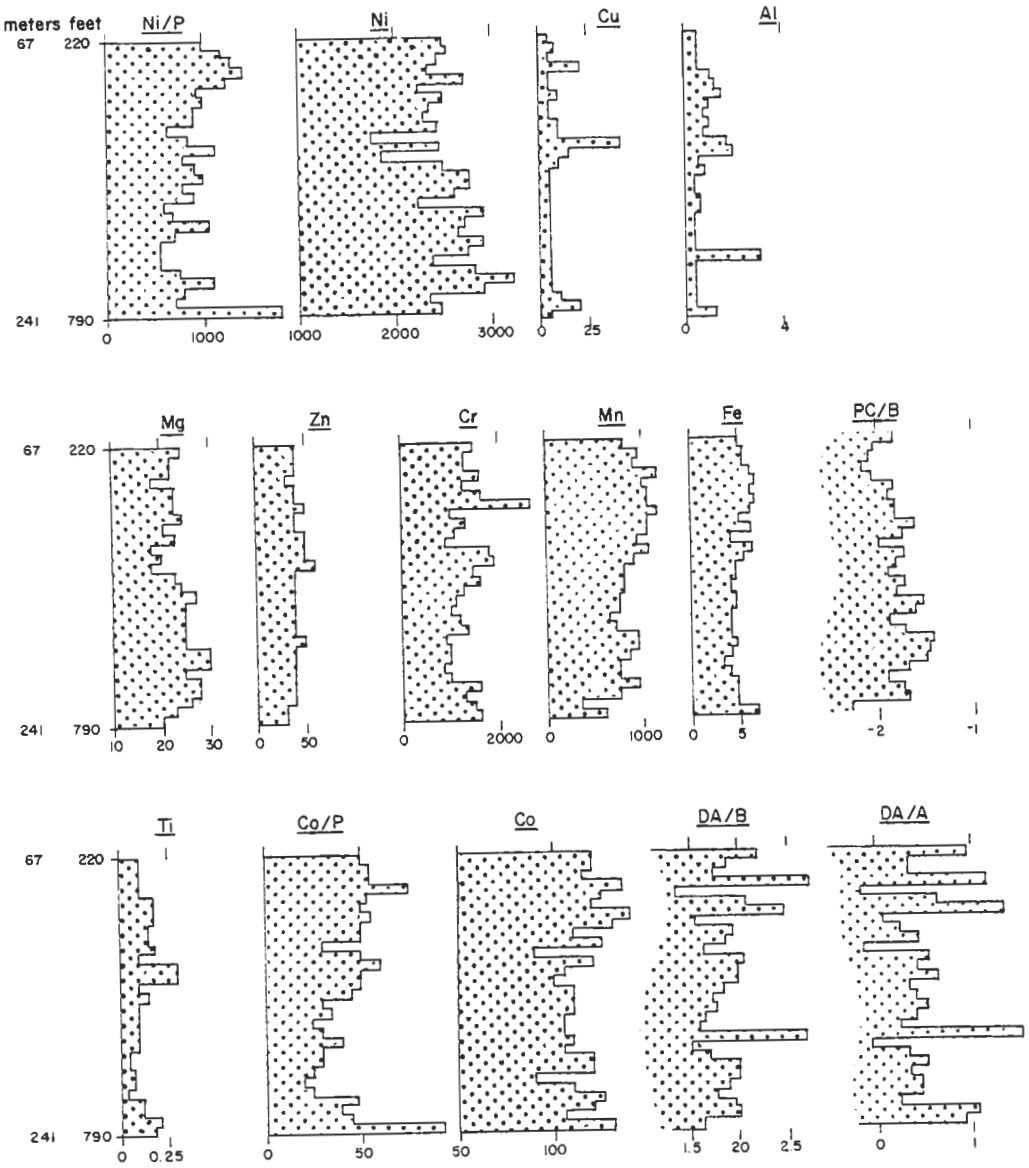

Fig. 69. Histograms of geochemical values, discriminant analysis A (DA/A) and B (DA/B) and principal component B (PC/B) scores for hole 20 at Bouchers. Vertical dimension not to scale. The analyses in total suggest that a single thick unit komatite was sampled.

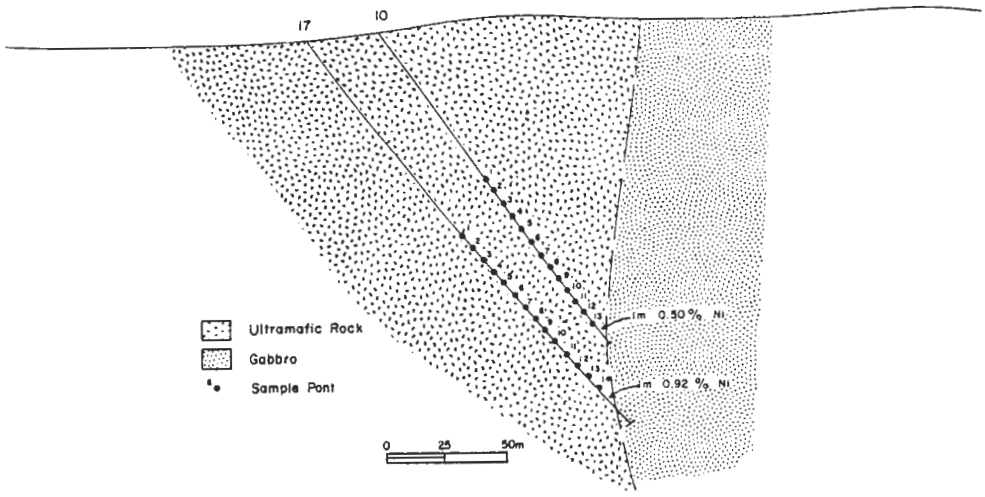

Fig. 70 . Cross section at Bouchers through holes 17 and 10 showing geology and sample points.

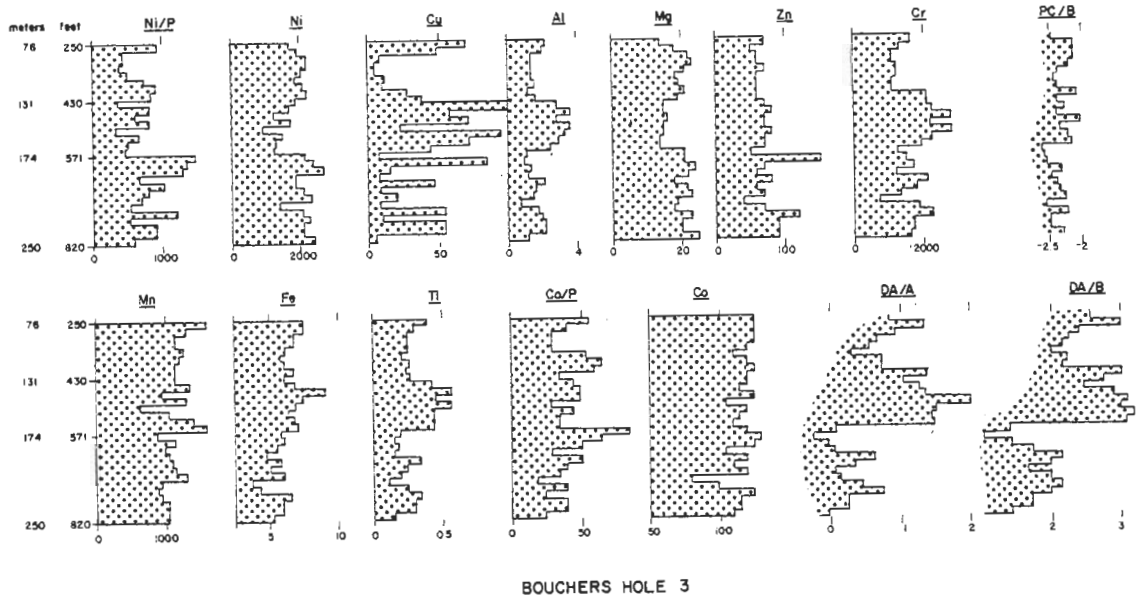

Fig. 71. Histograms of geochemical values, discriminant analysis A (DA/A) and B (DA/B) and principal component B (PC/B) scores, for hole 3 at Bouchers. Note the discontinuities in the values at 131 and 174 m. which indicate respectively a komatite boundary and an internal change from olivene cumulate to silicate liquid lava fractions. Depths are not to scale.

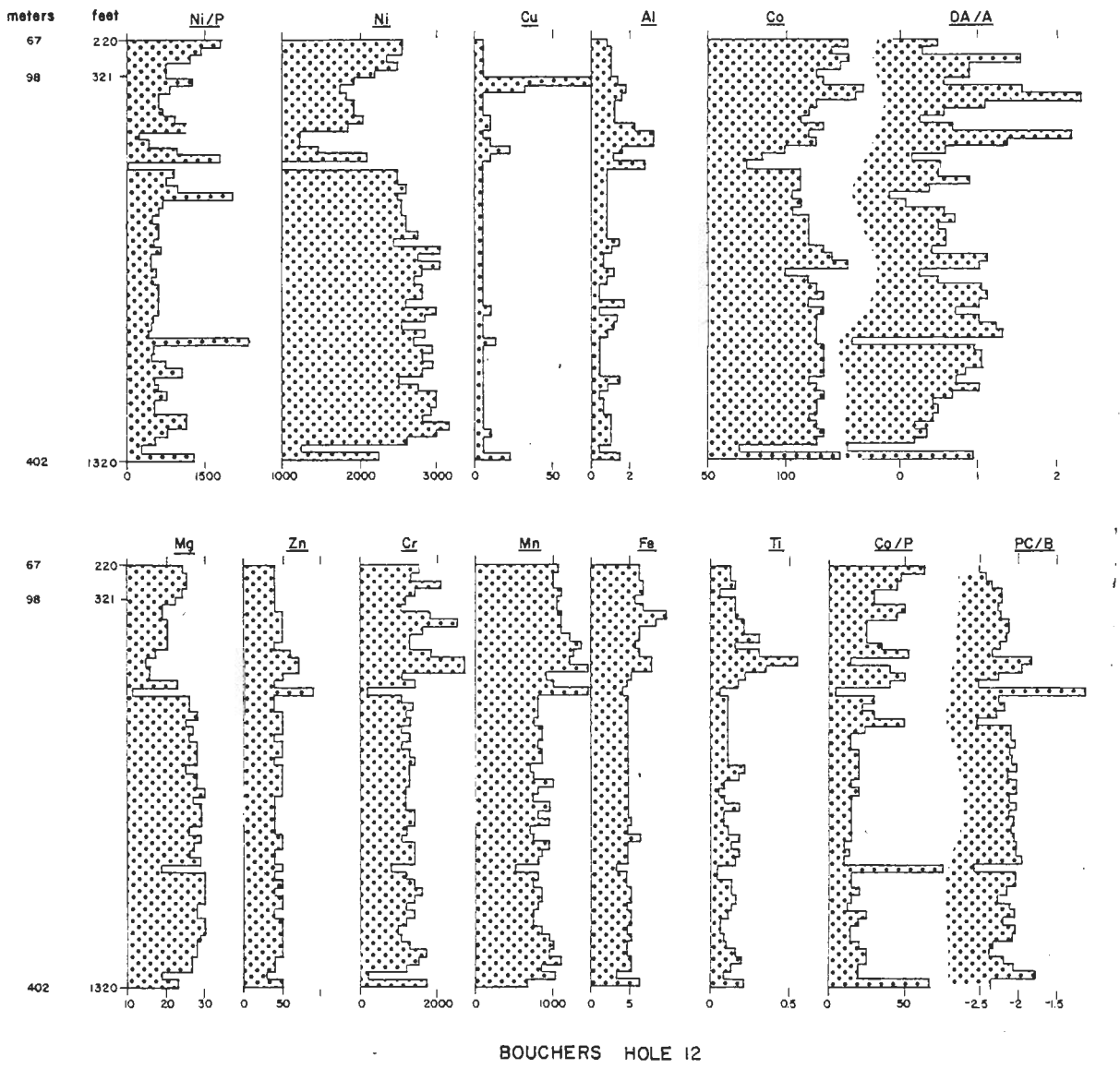

Fig. 72. Histograms of geochemical values, discriminant analysis A (DA/A) and principal component B (PC/B) scores, for hole 12 at Bouchers. A major change in values at 98 m. reflects the boundary between two komatiite units. Depths are not to scale. The values below 98 m. represent the upper silicate liquid and lower olivene cumulate sections of a single thick unit.

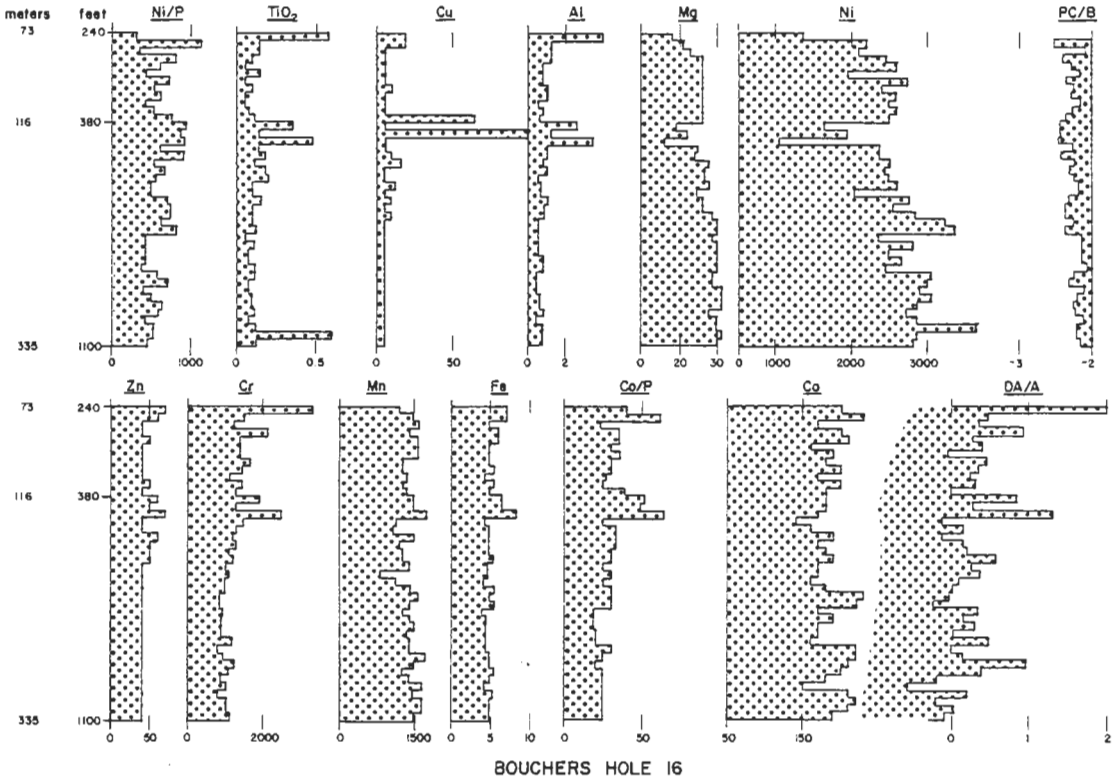

Fig. 73 . Histograms of geochemical values, discriminant analysis A (DA/A) and principal component B (PC/B) scores, for hole 16 at Bouchers. 116 to 335 m represents a single thick unit- with a relatively narrow upper silicate liquid section. Vertical dimension not to scale.

spinifex texture. The lower section between 174 and 250 m is higher in Ni and Mg and lower in Al, Cr, Fe and Ti and represents the peridotitic or olivine cumulate section of the komatiite. The changes at 131 and 174 m are accentuated by the canonical scores and the komatiite above 131 m has a lower mineralization coefficient than the peridotite portion of the unit. Over both komatiite units, Zn tends to increase towards the base of the lowermost unit and Fe and Mn tend to decrease. The mineralization coefficient increases as the basal contact is approached. Mean canonical scores for each hole with some mean chemical values are shown in Table 34. Hole 3 which is 230 m south of the mineralized zone, has the highest mean canonical score and thus the lowest mineralization coefficient. Mean Ni/Cr ratio is only 1.04. Hole 16 which did not reach the basal ultramafic contact has a low mean canonical score and thus a high mineralization coefficient. Hole 12 which was drilled to depth at the northern end of the property, had a moderate to high mean canonical score. These scores are tentatively interpreted as indicating that the potential for nickel sulphide accumulations is decreasing to the south but is still high with depth below hole 16. As hole 16 did not penetrate the basal contact, it did not adequately test this area.

A.3.2 Mt. Jewel, Mt. Jewel North and Red Dam

This area contains three groups within a contiguous komatiite ultramafic sequence along a strike length of 25 km. Nickel sulphides occur at Mt. Jewel and Red Dam but are not known at Mt. Jewel North. In addition, nickel sulphides occur north of Mt. Jewel at Ringlock. No samples were obtained from Ringlock. The regional geology is shown in Fig. 74. The areas flank an ellipsoidal structure in which mafic, ultramafic and sedimentary rocks wrap around a central core of intrusive granitic rocks. All known

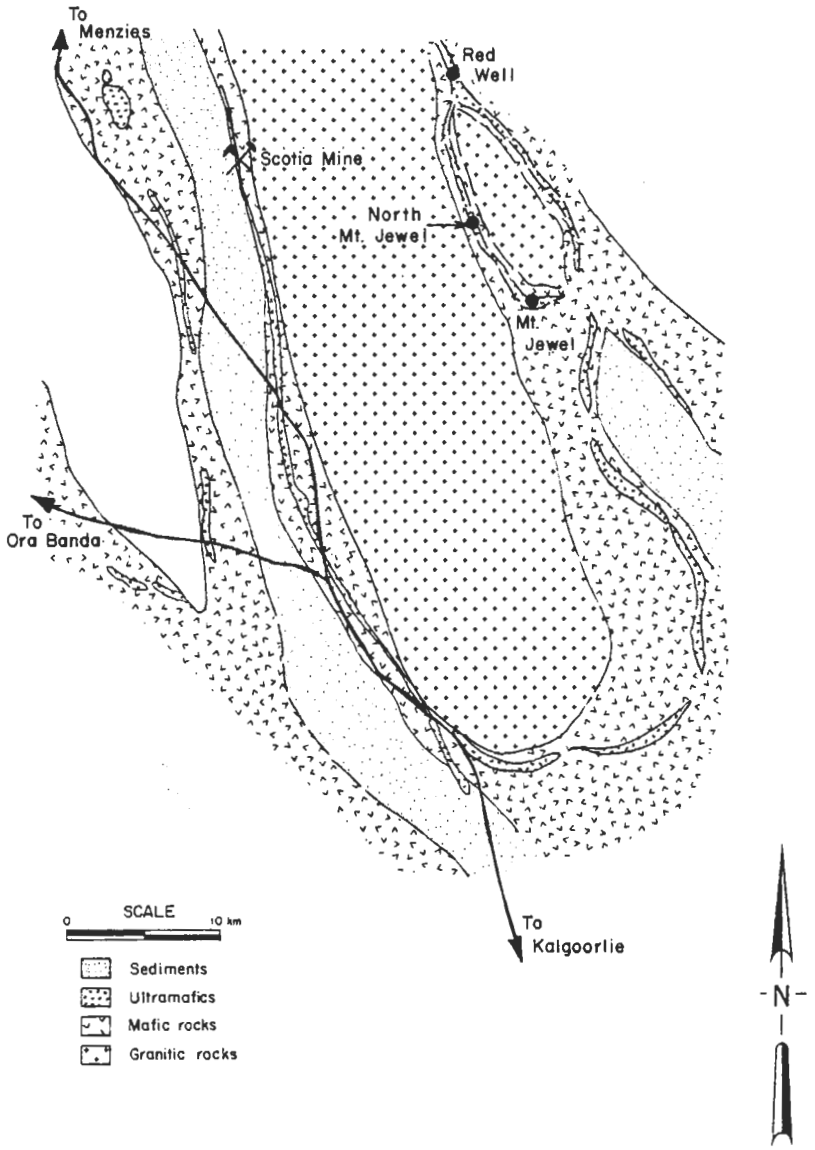

Fig.74 . Interpreted geology of the Scotia-Mt. Jewel area showing location of Scotia Mine, Mt. Jewel, North Mt. Jewel and Red Dam.

occurrences in this belt are small, usually of disseminated sulphides, and are low grade. The geochemical results for the above three areas are described below and they suggest that the entire strike length of this ultramafic sequence contains komatiite units which could host small nickel sulphide deposits.

Mt. Jewel nickel sulphide prospect is a small occurrence within a volcanic komatiite suite 48 km north of Kalgoorlie. The stratigraphic sequence is predominantly mafic-ultramafic with interbedded layers of sulphide rich sediment (Fig. 75). Cross-cutting intrusives of feldspar porphyry and doleritic rocks occur and dips are steep and to the north. Spinifex textures in core suggest that the ultramafic is south facing and that the northern contact is the basal contact of the sequence. Nickel sulphides occur at several horizons towards the center of the sequence, but the best intersection was only one meter grading 1.68% Ni and 0.28% Cu. Minor disseminated pyrite has been noted within the ultramafics.

Mean geochemical values for NiP and Ni are slightly lower (868 and 1905 ppm respectively) than the mean for all mineralized groups. All other variables, including chromium (1625 ppm) approximate the mean for all mineralized groups (Table 3). In the statistical analysis, 83% of samples were classified Mineralized by discriminant analysis A and 91% by analysis B. Average Ni:Cr ratio is 1.2 and Ni:NiP ratio is 2.2. Geochemical results for three holes are shown in table 35. These holes have penetrated a width of approximately 100 m and the geochemistry indicates that the komatiites are similar to the lowermost or thick units at Kambalda, with peridotitic or dunitic basal sections grading to pyroxene peridotite and spinifex textured tops. Hole 6 (Fig. 75) shows a gradation in samples 7 to 14 from a dunite at the base of the unit to pyroxenite at the top, overlain by high magnesium

Hole No.	Sample No.	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	Ni/Cr	Ni/Nip
DDH 4	1	1.48	1350	2450	3	8	0.80	1.80	21.20	60	1050	1050	5.00	0.09	68	125	2.33	1.81
	2	1.36	1038	2350	3	5	0.78	0.14	23.00	50	1150	900	6.30	0.10	60	135	2.04	2.26
	3	1.26	1950	2500	25	28	1.20	1.40	18.10	70	1400	800	6.30	0.15	93	135	1.78	1.28
	4	1.04	1175	2750	5	5	0.80	0.30	23.00	80	1550	850	5.90	0.13	58	135	1.77	2.34
	5	1.22	1363	2350	13	13	1.00	1.40	20.60	50	1250	600	5.60	0.14	73	115	1.88	1.72
	6	1.59	1000	2150	6	8	1.65	1.70	19.50	70	1550	950	6.70	0.22	65	130	1.39	2.15
	7	2.64	1200	1950	8	8	1.45	2.50	16.70	50	2450	1000	6.30	0.17	75	135	0.80	1.62
	8	1.17	713	2225	6	8	1.45	1.55	21.20	110	1450	1150	5.80	0.17	38	115	1.53	3.12
	9	0.10	1250	1950	6	8	1.45	2.75	19.00	150	950	950	5.50	0.17	60	105	2.05	1.56
	10	1.29	763	2150	6	8	1.45	1.70	20.60	60	1100	1050	6.30	0.17	43	115	1.95	2.81
	11	1.37	650	2375	3	5	1.35	1.40	21.80	60	1100	1100	6.70	0.20	40	125	2.16	3.65
	12	1.51	963	2225	3	5	1.20	1.40	21.80	50	1250	1050	6.00	0.14	50	115	1.78	2.31
DDH 6	1	3.53	113	1000	49	58	3.00	5.35	13.20	70	1500	1050	7.40	0.35	13	105	0.67	8.84
	2	0.81	2000	2250	14	18	1.00	0.27	22.40	60	1250	450	5.20	0.16	103	115	1.80	1.12
	3	0.70	1525	2150	4	5	1.45	0.19	22.40	40	1050	500	6.00	0.17	78	110	2.05	1.41
	4	1.62	838	2175	2.5	8	1.20	0.31	24.00	70	1400	850	5.50	0.21	45	110	1.55	2.60
	5	1.28	1550	2400	11	20	1.00	0.45	24.60	70	1350	950	6.00	0.10	68	130	1.78	1.55
	6	1.80	1388	1650	34	43	2.45	3.00	17.90	110	2150	1200	8.20	0.35	78	130	0.77	1.19
	7	1.81	588	2125	5	8	1.10	0.75	25.80	90	1650	1150	6.90	0.17	40	145	1.29	3.61
	8	1.66	800	2725	14	20	0.90	0.29	25.80	100	1700	1650	7.40	0.14	50	165	1.60	3.40
	9	3.00	525	2050	6	13	1.65	1.55	21.80	60	2350	1100	6.60	0.17	23	125	0.87	3.90
	10	2.32	838	1400	56	68	2.85	3.80	16.20	70	1650	1250	7.70	0.35	53	120	0.85	1.67
	11	3.83	63	375	3	10	5.05	6.40	9.80	130	1200	1500	9.30	0.62	15	100	0.31	5.95
	12	2.27	650	1025	89	100	3.60	4.95	13.20	230	2500	1450	8.20	0.48	43	115	0.41	1.58
	13	N.D.	50	400	9	25	7.10	7.00	8.00	120	700	1150	7.80	0.91	8	85	0.57	8.00
	14	3.51	63	350	8	18	7.60	6.40	6.30	90	700	1000	6.00	0.82	10	75	0.50	5.56
DDH 3	1	2.33	463	2200	5	8	1.30	2.05	21.80	70	1700	1100	6.30	0.20	23	125	1.29	4.75
	2	2.58	513	1675	61	75	2.20	3.80	18.10	60	1600	1100	6.50	0.32	33	115	1.04	3.26
	3	1.90	713	2325	6	15	1.65	2.85	20.60	80	1500	1200	6.60	0.20	33	120	1.55	3.26
	4	2.16	550	2100	3	5	1.75	1.80	21.20	60	1450	1250	7.40	0.26	25	135	1.45	3.82
	5	1.98	750	2400	8	10	1.75	2.05	21.20	70	1850	1150	7.40	0.26	35	135	1.30	3.20
	6	2.14	888	2150	5	13	1.55	2.05	21.80	70	1700	1000	6.30	0.22	43	125	1.26	2.42

Table 35. Geochemical analyses, canonical scores (B), Ni/Cr and Ni/NiP ratios for samples from three representative drill holes at Mt. Jewel. The samples represent several komatiite units separated by sediments or mafic volcanics. Samples 1 to 5 - Hole 4, and 2 to 5 - Hole 6 are typical examples of Mineralized thick units. Samples 7 to 14 - Hole 6, represent a composite thick unit with olivene cumulate lower section and silicate liquid upper section (sample 10), overlain by high Mg basalts.

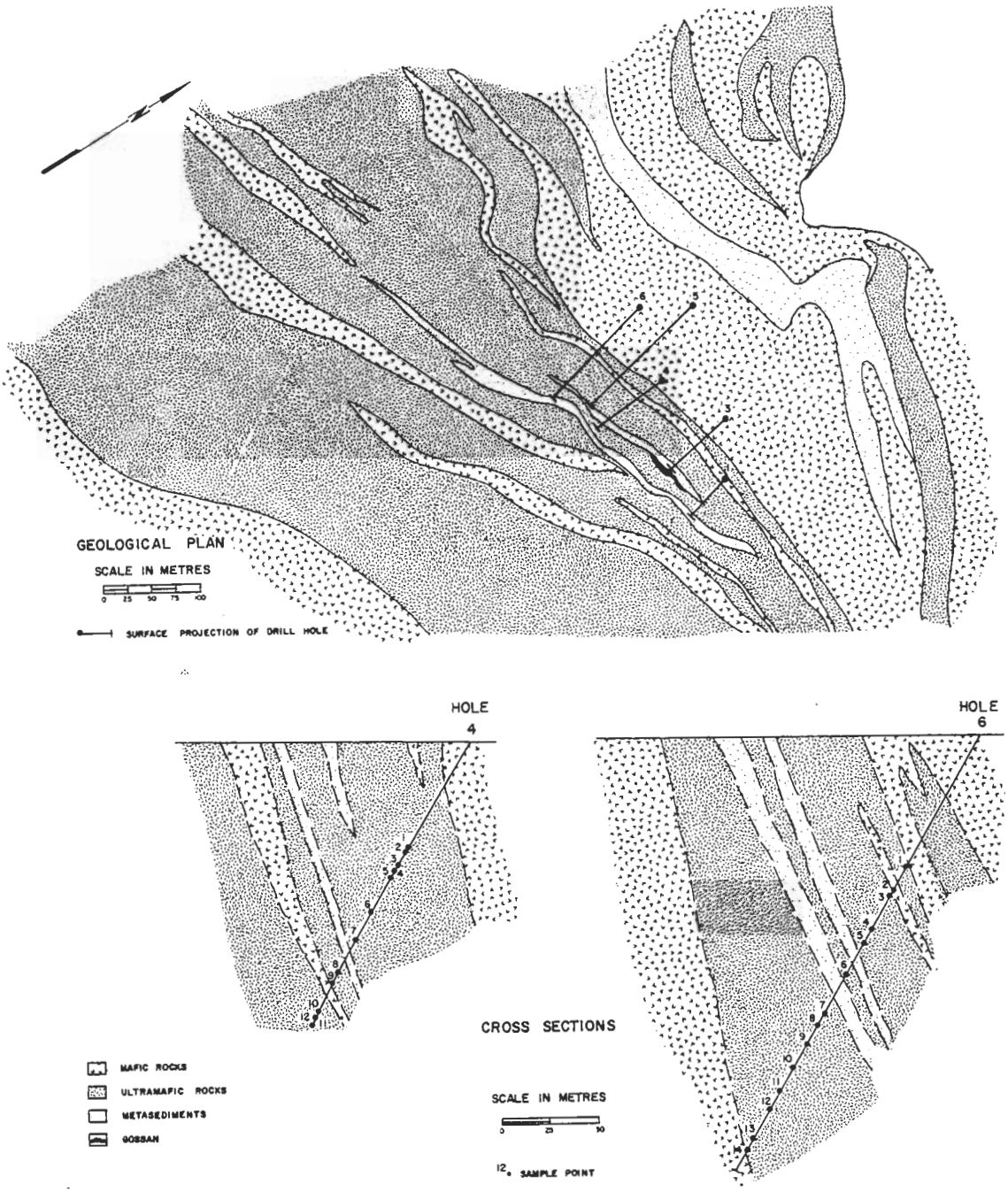

Fig. 75. Interpreted geology and cross sections of the Mt. Jewel prospect showing location of drill holes and individual samples.

basalt (samples 13 and 14). The komatiites represented by samples 2 to 6 (Hole 6), although dunites similar to samples 7 to 9, have different chemical signatures. These stratigraphically lower units (samples 2 to 6), have lower Ni/NiP ratios and higher Ni/Cr ratios, and a higher mineralization coefficient. Total nickel and magnesium values are essentially similar. Fe content is constant throughout and does not increase appreciably in the high Mg basalt.

Red Dam is a minor nickel sulphide occurrence 65 km north of Kalgoorlie. The actual size and grade of the occurrence is not known but it is probably comparable to Mt. Jewel. Ten spot core samples were obtained from two drill hoes, one of which intersected several feet of sulphide mineralization grading between 1% and 2% Ni. All samples are varieties of the serpentine-talc-carbonate association and chlorite is relatively uncommon. The ultramafic samples are reasonably homogeneous and represent several thick unit komatiites. One sample showed cumulate olivine textures. The samples mainly have a high mineralization coefficient with low Ni/NiP and high Ni/Cr ratios (Table 36). In the second hole, it should be noted that the ultramafic below the sulphide intersection has a different chemical character to the ultramafic above the sulphides (presumably the host). Although this lower ultramafic contains significant sulphur, as shown by both sulphur and NiP analyses, it is relatively high in chromium and low in total nickel and thus has a low mineralization coefficient or is Barren. The sample which contains significant nickel (1.79%) is also enriched in Cu (240 ppm) and Co (300 ppm) but contains approximately the same Mg and Fe and slightly less Zn and Cr than the bulk of the komatiite host.

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	S	Ni/Cr	Ni/NiF
102	336	0.92	1350	2350	2	6	1.15	0.04	21.00	60	1000	450	5.40	0.10	60	120	0.085	2.35	1.74
111	363	0.98	1425	2450	4	6	1.15	0.04	21.00	50	1050	500	6.10	0.10	85	150	0.12	2.33	1.72
125	410	1.10	1400	2350	4	5	0.94	1.10	20.10	60	950	900	5.60	0.07	60	130	0.155	2.47	1.68
141	463	0.80	3150	3500	46	49	0.55	3.40	19.40	50	850	500	5.25	0.07	45	130	0.38	4.11	1.11
164	538	1.46	2800	3350	74	67	0.57	3.80	17.40	40	950	800	4.20	0.05	77	130	0.35	3.52	1.20
120	394	1.34	2475	2675	46	43	0.98	0.66	21.50	40	950	700	6.10	0.07	115	170	0.18	2.81	1.08
143	469	1.19	3300	3300	142	148	0.65	0.06	22.00	50	1450	600	5.60	0.07	97	140	0.36	2.27	1.00
152	500	N.A.	1.58	1.79	120	240	0.62	0.01	21.00	20	700	550	5.70	0.05	155	300	1.93	25.60	1.13
173	566	3.26	1550	1925	26	27	1.40	1.00	18.80	50	3500	950	8.00	0.13	97	170	0.41	0.55	1.24
194	636	2.49	1475	1825	90	94	2.85	3.80	15.20	50	1900	850	6.50	0.17	52	120	0.64	0.96	1.23

Table 36 . These komatiite results from two core holes at Red Dam are typical of Mineralized sequences. The core holes are approximately 0.75 km. apart. Except for the two samples below the nickel sulphide in the second hole, the samples are excellent examples of komatiites with a high mineralization coefficient. The komatiite below the nickel sulphide has a different chemical signature with lower total nickel and higher Cr values - although containing appreciable sulphur.

North Mt. Jewel is situated approximately 55 km north of Kalgoorlie (Fig. 74). No nickel sulphides are known and this area was assigned to the Barren group for the statistical analysis. Twenty-seven samples represent a 56 m intersection of ultramafic in a single hole with a true thickness of the order of 40 m (Table 37). In discriminant analysis A only 43% and in analysis B, 45% of the samples were classified as Barren. This low classification would suggest that the Mt. Jewel North area had been incorrectly assigned. The drill hole analyses in Table 37 show that the hole penetrated a relatively narrow sequence of thin komatiite lavas (thin units) underlain (at 109.8 m) by a thicker komatiite unit, at least partly composed of olivine peridotite. This olivine peridotite has a high mineralization coefficient and appears to be a suitable host to contain nickel sulphide mineralization.

A.3.3 Scotia

Scotia is a small nickel sulphide mine situated 63 km north-northeast of Kalgoorlie near the northern limit of the Kalgoorlie-Norseman Nickel Province (Figs. 2 and 74). Published ore reserves at the commencement of mining were 1.13 million tons at 3.07% Ni and 0.25% Cu. Pyrrhotite-pentlandite ratio ranges from 0.5 in massive sulphides to 0.25 in disseminated sulphides. Total size of the sulphide body is apparently not appreciably greater than the published ore reserves.

The orebody occurs within a volcanic komatiite suite which has an intermittant strike length of 50 kms (Fig. 74) and is probably a part of the Mulgabbie Formation (Williams 1971) or Sequence 3 of Gemuts and Theron (1975). The Scotia greenstones are typically tightly folded on north-northwest axes and show evidence of low grade metamorphism. The

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co
78	256	2.96	750	1250	124	130	3.10	3.75	15.80	60	2450	1150	7.20	0.39	50	105
	264	2.99	1188	1700	162	163	3.80	3.75	15.40	60	2800	1100	7.40	0.60	75	135
	270	4.68	21	900	12	15	4.60	4.80	12.80	60	2600	1000	7.40	0.60	20	110
	275	2.59	675	1575	18	18	3.00	3.20	16.80	70	2400	1450	7.20	0.43	43	120
	280	4.86	55	675	2	5	5.10	5.40	10.80	70	2250	1000	8.20	0.70	13	120
	287	4.43	625	775	4	8	4.40	5.50	12.40	80	2950	1050	7.70	0.70	13	95
	292	1.87	613	1525	4	5	2.75	3.25	16.80	80	1700	1100	6.90	0.43	50	115
	295	2.14	950	1325	124	128	3.80	3.75	14.00	110	2000	1350	8.20	0.51	63	120
	297	2.73	450	900	54	65	4.30	4.80	12.00	130	2250	1100	7.40	0.60	35	100
91.5	300	2.01	663	975	40	40	3.40	5.10	14.50	110	1900	1250	6.60	0.48	38	85
	305	2.47	938	1125	288	278	3.40	4.00	13.60	120	2250	1650	8.70	0.37	83	125
	311	4.04	625	625	4	8	5.10	5.40	10.80	90	1600	1350	8.10	0.61	10	105
	321	2.19	663	1675	4	8	2.50	3.25	16.30	80	1750	1200	6.60	0.34	53	120
	345	1.98	1025	1375	44	45	3.40	3.75	15.40	90	2250	1150	7.40	0.46	55	100
	348	1.28	1375	1625	120	115	2.50	3.75	16.30	100	1550	950	6.40	0.34	68	100
	351	ND	950	1025	687	663	4.80	6.75	12.00	160	1850	750	8.40	0.51	138	175
	353	ND	950	1100	425	413	5.10	3.75	12.00	140	1800	600	8.70	0.60	130	170
109.8	360	0.76	1313	2400	12	13	1.10	0.05	21.00	40	1050	700	5.00	0.16	25	85
	370	1.00	1300	2300	10	10	1.10	0.03	21.60	40	1150	550	6.40	0.16	25	105
	380	1.18	1275	2075	6	8	1.10	0.03	22.80	30	1150	600	5.60	0.19	15	80
	390	1.84	863	2175	4	5	1.60	0.75	21.00	30	1200	1100	4.80	0.24	18	90
	400	3.08	988	1550	52	55	2.75	3.25	16.80	30	1900	900	5.60	0.37	58	115
	410	2.47	550	1425	4	8	3.00	2.90	16.30	100	2500	1150	6.30	0.34	43	105
	420	4.62	38	450	2	8	5.10	4.60	11.00	110	1850	1000	7.40	0.59	8	90
	425	2.19	563	1375	6	10	2.75	3.00	16.30	100	2100	1100	6.60	0.34	45	105
	429	1.87	1088	1450	56	55	3.20	4.00	13.20	140	2700	950	8.00	0.40	63	105
131.7	432	ND	450	475	363	360	0.80	1.75	1.40	110	100	1450	13.70	0.09	198	210

Table 37. Geochemical results and canonical scores (B) for samples from a single drill hole at North Mt. Jewel. The samples above 107 m. represent a sequence of thin units. Between 107 and 120 m. is a thick unit with strong mineralization characteristics in the olivene cumulate section. 107 to 109.8 m. probably represents the silicate liquid top of this thick unit. No nickel sulphides are known in this area.

regional stratigraphy from east to west is: granitic rocks; mafic-ultramafic sequence; granitic rocks. Scotia is separated from the nickel occurrences at Mt. Jewel and Red Dam by granitic rocks. According to Christie (1975) the orebody and associated rocks dip steeply west and form the eastern limb of a south pitching synclinal structure.

The geological sequence at Scotia Mine from east to west is as follows (Christie 1975): granite, mafic-volcanics 500 m; graphitic, pyritic sediments 5 m; komatiite sequence 600 m; sediments 600 m. The basal mafic volcanics are lineated tholeiitic basalts with intercalated tuffs, thin sediment layers and small ultramafic lenses. Overlying the volcanics is a thin sequence (up to 15 m) of graphitic slates and quartz-biotite schists intercalated with some basic tuffs. The sediments are bleached and silicified adjacent to the ultramafic and locally may contain fine-grained nickel sulphides.

The komatiite sequence which overlies the sediments is a composite komatiite lava pile. The orebearing unit is a lens shaped dunitic ultramafic, 500 m long and ranging up to 50 m wide. It extends to a depth of at least 450 m. The dunite has been serpentinized and extensively altered to talc-carbonate mineral assemblages. In four samples, estimates of original olivine content varied from 70% to 85%. Only two of the seven samples collected were strongly magnetic and three samples were non-magnetic. The sulphide zone at the base of the host dunite is separated from the footwall sediments by a thin (15 cms) chloritic zone composed largely of amphibole and chlorite (Christie 1975). The ore host (thick unit) komatiite is separated from the overlying metamorphosed thin units which comprise the bulk of the sequence by a zone of metamorphosed sediments and mafic volcanics. These thin units have well preserved spinifex and

flow breccia structures, although the komatiites are completely altered to assemblages dominated by antigorite, chlorite and magnesium amphibole. Minor intercalated sediments and mafic volcanics up to 600 m long and 20 m thick are also present.

The mineralization is located in a centrally placed footwall embayment; has a length of 150 m; a thickness of 20 m and a depth of at least 370 m. The orebody averages 10% sulphides and has a grade of 3% Ni at a 1% cutoff. A discontinuous footwall layer of massive sulphides up to 2 m thick and averaging 15-20% nickel is overlain by up to 20 m of disseminated sulphides averaging 1% to 7% Ni. The entire ore host komatiite contains minor quantities of pentlandite (Christie, 1975). Within the mineralization, large olivine grains (1 to 4 m) are contained in a mat of interwoven serpentine needles. The average mineralogy of the massive ore is 60% pentlandite, 30% pyrrhotite, 5% pyrite, 5% magnetite, 0.5% chalcopyrite and minor chromite. The disseminated ore contains similar mineralogy to the massive ore but the percentage of pentlandite (up to 80%) increases towards the top of the ore.

Seven rock samples were obtained from underground workings (Table 38). One sample (2) is obviously from within low grade disseminated ore but all other samples are from the komatiite overlying the ore zone. All samples except one have a moderate to high mineralization coefficient and the single exception is a borderline case with a canonical score of 2.53. All samples chemically (Table 38) are olivine peridotites or dunites (Mg 20% to 27%) and most have mineralized characteristics such as high Ni/Cr ratios and low Ni/NiP ratios. Sulphur contents vary from 0.065 to 0.78%. The komatiite with disseminated mineralization has similar values of Mg, Cr, Fe and Zn, 50% more Co and 100% more Ni and Cu than the mean of the remaining samples. The geochemistry of the Scotia ore host ultramafic is regarded as typical of a komatiite with a very high mineralization coefficient.

A.3.4 Nepean

Nepean is a small nickel sulphide mine within an isolated greenstone inlier surrounded by granitic rocks 26 km south of Coolgardie (Fig. 2). Total size of the nickel sulphide bodies is not known but is probably of the order of one million tons grading in excess of 3% Ni. Metamorphism is of medium to high amphibolite facies and the rock sequence at Nepean is regarded as a former sequence of intermediate to basic volcanics with minor acid volcanics, intercalated pelitic sediments and cherts, and broadly conformable dolerite, gabbros and ultramafics (Sheppy & Rowe 1975). The sequence is intruded by post metamorphic, flat lying pegmatites and aplites.

The geology at Nepean is illustrated in Figs. 76 and 77 (after Sheppy and Rowe 1975). The rocks dip steeply, face west and a section from east to west through the mine would be as follows: Granitic rocks; overlain by thin chlorite rich komatiite ultramafic; fine-grained amphibolites (metabasalts); thin chlorite rich komatiite; fine and coarse-grained amphibolites (metabasalts); thin ore bearing, dunitic komatiite (thick unit); fine-grained amphibolites and pyrrhotitic metasediments; thick chlorite rich komatiite with some peridotitic and dunitic layers (thin units); fine-grained amphibolites (metabasalts) with some metasedimentary horizons; granitic rocks. Irregular pegmatite bodies intrude all sequences.

The amphibolites can be divided into two groups both of which now consist of hornblende-plagioclase-cummingtonite-quartz. These are fine-grained metabasalts which are dominant and coarser-grained metagabbros and metadolerites, which characterize the amphibolites underlying the ore zones. The metasedimentary rocks include assembalges such as biotite-plagioclase-quartz-staurolite-sillimanite. Cherts have been converted to quartz-plagioclase-pyrrhotite-chlorite-cordierite-ankerite rocks.

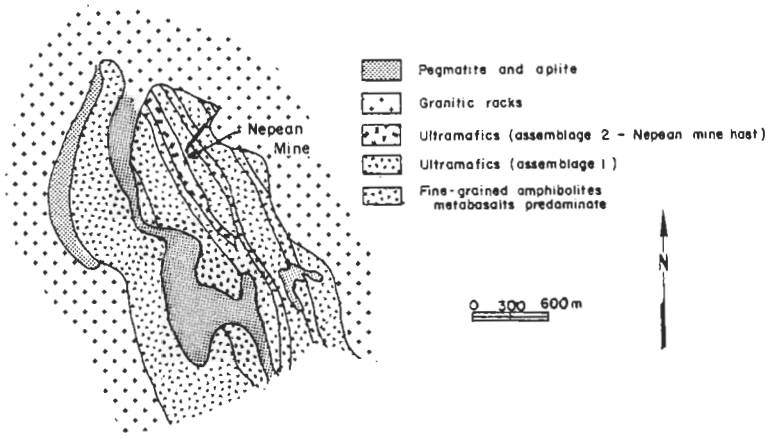

Fig. 76. Geology of part of the Nepean inlier (after Sheppy and Rowe, 1975).

Sample	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	S	Ni/Cr	Ni/NiP
1	0.06	2350	3200	48	47	1.05	0.04	24.00	90	1050	650	5.45	0.09	50	120	0.24	3.05	1.36
2	0.41	7000	7460	76	75	1.60	0.08	24.25	90	1350	1050	5.80	0.07	120	180	0.78	5.52	1.07
3	0.03	2475	3300	34	38	1.15	0.06	24.00	90	1250	750	5.60	0.10	52	110	0.25	2.64	1.33
4	0.49	2225	2900	42	43	1.75	0.04	20.10	60	950	650	5.15	0.13	75	140	0.22	3.05	1.30
5	0.86	1500	2275	38	39	1.40	0.21	24.50	50	1000	570	5.70	0.10	57	120	0.145	2.27	1.52
6	2.53	450	2300	2	5	1.15	1.00	26.80	40	1200	950	5.90	0.10	22	140	0.075	1.92	5.10
7	1.43	950	2300	10	14	1.15	0.33	24.00	60	1250	750	5.15	0.10	40	120	0.065	1.84	2.42

Table 38. Geochemical analyses, canonical scores (B) Ni/Cr and Ni/NiP ratios for seven samples from the Scotia Mine. Note that most samples have high to very high coefficients of mineralization. In sample 2, which represents disseminated nickel sulphide mineralization - Ni, Co, Cu and S are enriched relative to rest of the komatiite. Mn and Cr may be slightly enriched, but Al, Mg, Fe and Ca contents are the same in the disseminated sulphide section and the mainly sulphide free komatiite host. The lowest Ni/Cr ratio value is 1.84.

Sample	Canonical score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	S	Ni/Cr	Ni/NiP
1	0.93	1200	2175	10	13	0.95	0.05	25.10	30	950	1050	4.95	0.07	25	80	0.165	2.29	1.81
2	0.64	1775	2000	4	7	0.92	0.39	25.50	20	800	700	4.95	0.07	102	150	0.21	2.50	1.13
3	0.94	625	1350	4	6	0.97	0.08	26.80	20	800	400	3.60	0.07	7	40	0.17	1.69	2.16
4	2.32	2125	2375	4	6	1.75	1.20	21.50	40	1800	1300	6.00	0.10	130	200	0.195	1.32	1.11
5	3.03	375	1350	20	21	3.20	3.65	17.10	80	2350	1400	8.00	0.20	27	130	0.045	0.57	3.60
6	2.88	1900	1900	72	66	2.50	4.45	16.60	90	2050	1300	7.10	0.17	95	140	2.05	0.93	1.46
7	2.50	125	1375	200	280	0.73	20.2	12.80	30	450	800	3.95	0.20	5	100	0.19	3.06	11.00

Table 39. Geochemical analyses, canonical scores (B) Ni/Cr and Ni/NiP ratios for seven samples from Nepean Mine. Samples 5 and 6, which canonical scores and Ni/Cr ratios indicate are Barren, were taken from an overlying komatiite sequence (assemblage 1,), which is separated from the ore host by sediments.

The komatiites can be divided into two mineral assemblages (Sheppy and Rowe 1975):

1. Tremolite-chlorite-clinopyroxene komatiites, with olivine and antigorite in some horizons, characterize non-ore bearing ultramafics. Minor sections show relict spinifex textures and metamorphic olivine and these sequences probably represent thin units. Only minor amounts of serpentine minerals are present (assemblage 1, Fig. 77).
2. Serpentinite ultramafics (nickel sulphide host), almost wholly composed of serpentine, and considered by Sheppy and Rowe (1975) to have originally been intrusive peridotites (assemblage 2, Fig. 77).

The upper part of one of the ore host komatiites is tremolite-chlorite ultramafic and probably represents the upper pyroxenitic (silicate liquid) part of a thick unit. This komatiite is similar to the thick units at Kambalda or ultramafic A komatiites at Windarra South. The upper amphibole-chlorite zone passes into central and basal zones comprising olivine (with serpentine pseudomorphs) and orthopyroxene (partially replaced by talc) together with lesser interstitial chlorite and minor amphiboles. Sulphides are concentrated at the base of the unit. The peridotitic core contains 70% pseudomorphs after olivine and 20% after orthopyroxene and talc. Magnetite, released during serpentinization, enhances the texture by outlining primary olivine grains.

Sheppy and Rowe (1975) describe a typical ore cross section as:

1. 0.75 m of 'massive' ore at the base of the unit and comprising approximately 60% sulphides with serpentine or olivine matrix and only accessory magnetite;
2. 0.45 m of 'triangular' disseminated ore containing 10-40% sulphides, more abundant magnetite than in massive ore and randomly oriented blades of serpentine which impart the characteristic texture; and
3. 0.3 m of approximately 5% fine disseminated sulphides in serpentinite, magnetite being fairly abundant.

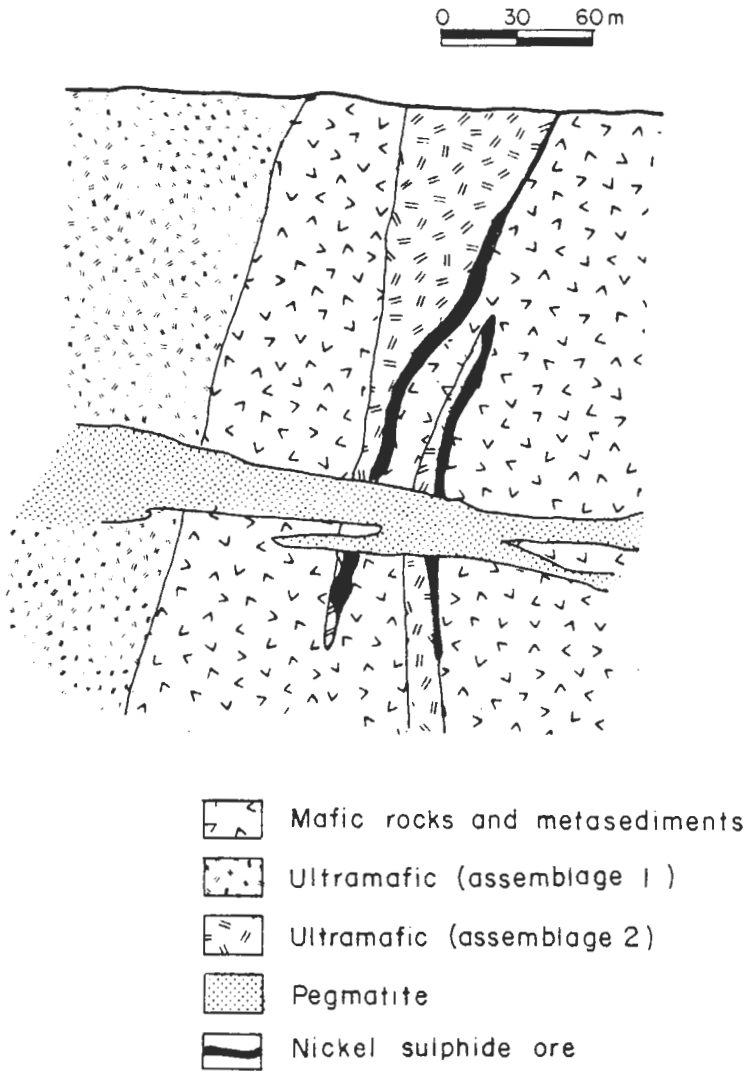

Fig. 77. Diagrammatic cross section of the Nepean Mine showing approximate relationships of rock units sampled. Samples 5 and 6 are from assemblage 1, samples 1 to 4, and 7 are from assemblage 2

A sharp boundary is often present between 1 and 2 above, and either unit 2 or 3 can be missing in some ore sections. The nickel copper ratio of the ore is 15.1 and nickel cobalt ratio is 60:1. The ore occurs close to, but not in direct contact with the underlying amphibolites. Maximum sulphide concentration is 0.5 m from the contact. The ore is composed of 50-60% pentlandite, 20% pyrrhotite, 20% pyrite with minor chalcopyrite, chromite and magnetite. Near the top of the ore zone magnetite is markedly enriched relative to sulphides. Chromite is partly altered to valleriite throughout the ore zone (Hudson 1976). Above zone 2 of Sheppy and Rowe (1975), in the disseminated sulphides, pyrite is absent and as sulphide abundance falls, pentlandite progressively give way to millerite and heazlewoodite.

Eight samples were obtained from underground openings at Nepean. Samples 1 to 4, and 7 are from assemblage 2 (Fig. 77), the ore bearing thick unit and samples 5 and 6 are from the overlying assemblage 1, the non ore bearing thin units (Table 39). All samples (except 7), from the ore bearing komatiite have a moderate to high coefficient of mineralization, whereas the samples from assemblage one (non ore bearing) are barren in terms of mineralization coefficient. Note that sulphur is extremely high (2.05%) in one barren ultramafic sample indicating that sulphur on its own is not a good indicator of mineralization. Samples 5 and 6 have Ni/Cr ratios of less than 1 (0.57 and 0.93) in contrast to all other samples which are greater than one. Sample 7 is a low Mg and Cr pyroxenite from the top of the ore bearing komatiite and although low in NiP and CoP has a moderate total sulphur content (0.19%). This indicates that the sulphur was introduced relatively recently. Samples 1 to 3, from the lower part of the ore bearing komatiite, based on Mg content, can be regarded as a dunite rather than a peridotite, but this is probably caused by the high metamorphic grade and presence of metamorphic olivine.

The analyses support the contention that one komatiite sequence at Nepean is a nickel sulphide host and the other is barren. Nepean differs from Kambalda, Windarra South and other deposits of the volcanic association in one point only; the ore host is separated from the overlying komatiite thin unit sequence (assemblage 1, Fig. 77) by mafic and sedimentary rocks. The evidence is inconclusive as to whether this means that:

(a) ore host komatiites were extruded as individually thick lavas, followed by extrustions of mafic rocks, deposition of chemical sediments and finally by extrusion of a komatiite lava pile; or

(b) that these ore bearing komatiites were the final phase in the sequence of events and instead of being intruded at or near the footwall of the komatiite lava pile, as at Kambalda, Scotia, etc., were intruded within the footwall mafic rocks.

A.3.5 Jubilee

The Jubilee prospect (Fig. 2) is situated approximately 60 km northeast of Kalgoorlie within the eastern sector of the Wiluna Norseman belt (Gee, 1975). It is a small occurrence of nickel sulphides in an apparently intrusive komatiite ultramafic. According to Williams (1970), Jubilee falls within Volcanic Cycle 3 or the Kalpini Formation and is structurally within a major syncline. Ultramafic rocks are found near the base of Cycle 3 but according to Gemuts and Theron (1975), the Kalpini Formation is not considered prospective for nickel sulphides.

The Jubilee ultramafic is a plug-like body, approximately 3 km by 1.5 km. Nickel sulphides are present near the northern contact but no details are available of the grade or size of the deposit. Twenty-three spot core samples were obtained from six core holes and represent a 70 m width of

Hole No.	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	Ni/Cr	Ni/NiP
F	2.57	188	2650	2.5	5	0.64	0.06	24.60	60	1150	1050	3.80	0.07	38	165	2.30	14.10
	2.04	100	2550	29	45	0.72	0.23	22.30	40	1300	1000	6.10	0.07	13	70	1.96	25.50
	2.26	288	2600	5	8	0.84	0.92	22.00	50	1400	800	4.60	0.09	78	135	1.86	9.02
	0.81	288	2550	14	18	0.78	0.03	21.40	40	1000	600	6.30	0.07	50	85	2.55	8.85
	1.13	650	2900	18	15	0.61	0.08	22.80	50	1250	750	4.60	0.07	90	120	2.32	4.46
	1.39	2900	5800	159	150	0.88	0.19	20.30	40	1450	1000	6.90	0.06	180	210	4.00	2.00
	0.86	275	2500	20	23	1.00	0.04	21.10	40	1150	400	5.10	0.09	48	75	2.17	9.09
G	2.78	50	2075	5	8	0.80	0.90	18.80	50	1000	600	4.80	0.08	8	95	2.08	41.50
	2.79	50	2000	2.5	5	0.79	1.05	18.50	60	1100	1150	5.00	0.03	5	80	1.82	40.00
	3.31	25	2150	3	5	0.92	0.54	18.00	60	1250	600	4.40	0.03	5	100	1.72	86.00
	3.36	25	1800	2.5	5	0.73	0.89	16.50	70	900	1000	3.30	0.03	5	95	2.00	72.00
	3.07	50	2000	2.5	5	0.82	1.85	18.30	60	1100	800	4.30	0.03	8	95	1.82	40.00
C	4.90	125	1800	124	130	1.95	5.55	14.30	40	2600	1050	5.40	0.03	28	155	0.69	14.40
	2.79	88	2150	21	30	0.78	6.95	14.50	40	750	800	4.30	0.03	33	110	2.87	24.40
E	2.38	125	1850	63	73	0.64	3.35	18.00	40	650	800	4.80	0.03	13	90	2.84	14.80
	2.75	88	2250	34	35	1.20	2.50	16.50	40	900	750	4.80	0.03	10	100	2.50	25.50
D	2.97	775	2350	119	138	1.45	2.00	15.40	40	2400	1200	6.20	0.03	28	95	0.98	3.03
	1.85	150	1825	19	20	0.89	0.06	18.00	50	900	750	4.60	0.03	20	95	2.02	12.20
B	2.44	513	2200	76	83	4.80	0.08	12.20	90	3900	650	10.70	0.03	48	125	0.56	4.29
	4.75	25	1900	78	115	1.45	0.66	16.80	40	2050	650	5.50	0.03	5	105	0.96	76.00
A	1.57	588	3625	16	20	0.50	0.20	17.80	60	950	1050	5.00	0.03	60	160	3.81	6.16
	2.26	500	2100	19	28	1.80	1.85	18.50	90	2100	1200	6.30	0.24	35	115	1.00	4.20

Table 40 . Shows komatiite sample results from seven core holes at Jubilee. Jubilee is considered to be a Mineralized intrusive komatiite sequence, but is a small and isolated occurrence in a greenstone belt which is not known to host nickel sulphides elsewhere. The sulphur content (NiP) is relatively low. If it was not known that nickel sulphides occur at Jubilee, on the basis of the canonical scores and analyses, the area could be considered of doubtful potential and probably Barren. The geochemical results show some similarities to Bullfinch.

ultramafic. Mean geochemical value for nickel (2437 ppm) is slightly higher than the mean for all Mineralized groups (2220 ppm), but the mean for NiP (357 ppm) is significantly lower (mean for mineralized group is 1027 ppm). This is reflected in a high Ni to NiP ratio of 6.8. Nickel to chromium ratio is 1.7. In discriminant analysis A, 82% of samples and in analysis B, 50% of samples, were classified as Mineralized. This is the only group in which the percent correctly classified is reduced by analysis B and is caused by the greater influence in analysis B of NiP. Canonical scores and geochemical analyses are listed in Table 40. These komatiites are extremely low in TiO_2 and relatively low in Fe as well as NiP. Chemically they vary from pyroxene peridotites to dunites. Without additional geologic and petrographic data it is not possible to draw further conclusions from the data. However, it should be stressed that Jubilee is unique among the Mineralized groups in having exceptionally low NiP values.

A.3.6 Credo

The Credo ultramafics are a part of a volcanic komatiite suite in which extensive exploration, including auger, rotary and diamond drill holes failed to locate significant sulphides. The ultramafics are mainly from the serpentine-tremolite-chlorite suite and four samples showed well developed plate and random spinifex textures. The Credo discriminant analysis results do not fit well as either Barren or Mineralized. In analysis A, 58% of samples and in analysis B, 67% of samples were classified as Barren. Thus 33% in analysis B were classified as Mineralized. Mean geochemical results are approximately equivalent to the mean values for all barren groups (Table 3). Detailed geochemical results with respective canonical scores are displayed in Table 41. These komatiites have moderate to low Ni and Mg,

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	S	CoP	Co
99	298	2.30	475	1350	120	120	4.75	2.80	15.60	180	2550	1200	7.30	0.065	35	120
	355	2.47	700	1950	2	4	1.35	2.30	18.20	60	1650	1000	5.90	0.025	25	120
	555	3.04	375	1350	18	17	2.75	4.45	15.30	70	2100	1300	6.60	0.025	27	120
	604	3.72	275	1050	266	280	3.70	4.45	13.60	80	2500	850	7.80	0.065	32	120
	729	2.33	400	2000	2	2	1.75	2.30	19.00	50	1900	850	5.45	0.010	15	120
	777	3.21	600	1325	4	5	3.45	1.60	16,60	60	3500	1350	8.20	0.045	57	130
	930	3.03	525	1250	126	128	2.90	4.45	15.05	120	2800	1400	7.40	0.080	37	120
	1054	2.68	725	1950	2	5	1.45	2.25	19.00	50	1800	1200	5.20	0.010	30	110
	1102	3.65	350	1200	34	34	2.85	5.60	13.50	80	2550	1250	7.90	0.065	25	140
359	1178	3.16	375	1650	4	5	2.40	3.15	17.00	80	2800	1600	7.20	0.010	22	130
135	444	2.35	625	1800	8	9	2.00	3.25	17.60	100	2100	1600	6.00	0.300	35	130
149	488	4.89	25	800	16	17	3.60	7.25	12.30	100	1950	1550	6.90	0.005	5	130

Table 41. Geochemical results and canonical scores (B) from two core holes at Credo. These komatiites are moderate magnesium, and moderate to low nickel lavas, probably mainly thin units. Some samples show low mineralization coefficients but in total the samples suggest the sequence as sampled is Barren.

moderate NiP and moderate to high Cr contents. The moderate values of NiP give rise to Ni to NiP ratios in the mineralized range, but Ni to Cr ratios are invariably less than one and thus in the barren range. Sulphur contents are low with the exception of a single sample. Four of the canonical scores are less than 2.5, which places these samples in the low coefficient of mineralization range. However, all the above samples are barely into the mineralized range and consequently, when considered with the remaining samples, do not constitute significant mineralization potential. There is little doubt that this group was correctly designated as Barren.

A.3.7 South Bulong/North Bulong

The South Bulong ultramafic is within the Morelands Formation (Williams, 1970). Four holes were situated along a strike length of 1400 m of ultramafics at South Bulong and the remaining hole was sited at North Bulong, approximately 30 km north of South Bulong. The komatiite sequence at South Bulong consists mainly of extrusive, magnesium deficient komatiites. Other rock types include chloritized and carbonatized basic volcanic rocks, some of which contained minor accumulations of pyrite and pyrrhotite. At North Bulong the drill hole contained appreciable quantities of metamorphic bladed olivine and visible disseminated sulphides.

76% of samples were classified as Barren by discriminant analysis A and 85% by analysis B. Average chemical values approximate the means for all barren groups (Table 3). Mean Ni to Cr ratio is 0.6 and Ni to NiP ratio is 5.0. The analytical results in Table 42 confirm that South Bulong is a sequence of low nickel, sulphur and magnesium komatiite lavas (thin units). North Bulong (Table 43) contrasts somewhat with South Bulong in that it has a peridotite section and has high NiP (and thus sulphur) and

Depth Meters	Depth Feet	Canonical Score	Nip	Ni	Cup	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	Ni/Cr	Ni/NiP
65.5	215	2.82	400	1600	10	20	3.60	4.25	15.00	60	1800	1200	7.50	0.34	40	120	0.89	4.00
	240	2.74	325	1600	38	50	3.20	3.40	15.40	70	1800	1250	7.50	0.30	35	120	0.89	4.92
	260	2.85	287	1300	78	95	3.00	5.20	16.00	60	1600	1050	7.20	0.21	40	110	0.81	4.53
	280	3.64	62	1300	46	65	4.20	6.30	14.50	100	2400	1350	8.60	0.30	20	115	0.54	20.96
	300	1.41	525	2175	4	10	2.10	0.60	21.10	60	1150	950	6.20	0.18	48	110	1.89	4.14
	320	1.78	800	2400	30	35	1.65	1.35	19.40	60	1600	1000	5.50	0.15	73	120	1.50	3.00
	340	2.97	237	1450	28	35	3.85	4.90	14.50	70	2000	1400	9.40	0.36	35	125	0.73	6.10
	360	3.16	475	1500	12	20	3.20	6.65	13.00	80	2900	1100	7.50	0.36	45	115	0.52	3.16
	380	3.09	450	1350	80	93	3.60	4.75	14.50	80	2600	1300	7.70	0.36	53	120	0.52	3.00
	400	3.07	337	1250	120	130	3.60	5.20	13.50	70	2200	1050	6.90	0.36	38	100	0.57	3.71
	420	3.04	775	1600	22	33	3.20	3.80	13.50	60	2600	1300	8.30	0.30	55	125	0.62	2.06
	440	3.58	250	1150	186	195	3.60	4.55	13.50	80	2900	1350	7.20	0.36	30	100	0.40	4.60
143.3	470	2.74	800	1400	50	60	3.00	4.40	13.00	70	2000	1150	6.90	0.30	60	120	0.70	1.75

Table 43 . Geochemical analyses, canonical scores (B), Ni/Cr and Ni/NiP ratios for samples from a core hole at North Bulong. The komatiites are mainly moderate to low in Mg and Ni and are probably mainly thin units. The 5th and 6th samples represent a thick unit peridotite with moderate mineralization coefficient. However, on the basis of these and other samples the komatiite sequence appears to consist mainly of thin units and is unlikely to host significant nickel sulphide deposits.

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	Ni/Cr	Ni/NiP
79.3	260	2.89	38	850	2	5	2.00	2.80	16.50	100	1050	1150	6.10	0.20	10	85	0.81	22.9
	280	3.42	38	850	124	128	6.20	2.10	16.50	110	1350	1400	10.00	0.49	8	120	0.63	22.9
	300	4.98	50	1500	34	45	3.40	8.90	10.60	100	3900	2000	8.30	0.29	10	130	0.38	30.0
	320	4.46	50	1100	52	68	3.70	5.85	15.00	80	2450	2050	7.20	0.35	5	100	0.45	22.0
	340	3.48	75	1550	24	28	3.70	3.30	16.50	70	2500	1150	8.80	0.26	18	115	0.62	20.7
	360	3.09	75	1125	32	35	2.80	3.50	16.50	60	1100	1150	5.80	0.26	8	90	1.02	15.0
	380	2.97	738	1850	144	165	4.00	5.05	15.00	90	2950	1100	7.70	0.36	40	130	0.63	25.1
	400	4.43	50	800	78	103	5.60	4.90	13.00	100	2300	1650	9.10	0.59	8	110	0.35	16.0
	420	4.26	63	1050	102	115	5.00	4.90	13.00	100	2250	1450	8.80	0.53	5	115	0.47	16.9
	460	4.69	63	1500	44	55	5.50	4.40	13.00	80	3200	1200	8.00	0.40	5	125	0.47	24.2
	480	4.21	75	1075	118	115	4.90	4.10	14.50	90	2750	1300	8.30	0.49	8	110	0.39	14.3
	500	4.00	75	950	10	15	3.20	2.95	16.00	80	2450	750	6.90	0.30	5	90	0.39	12.7
	520	4.82	25	750	56	73	5.60	7.65	12.00	110	2700	1800	9.10	0.50	5	100	0.28	30.0
164.6	540	5.08	50	1200	132	170	5.00	6.50	11.60	100	3600	1650	9.40	0.42	5	120	0.33	24.0

Table 42 . Komatiite results from a single core hole at South Bulong. These komatiites are very low in sulphur (NiP), are low in nickel and can be regarded as Barren

total Ni values. Except for the narrow peridotite, chromium results are similar for both areas. The two peridotite samples show moderate to high mineralization potential and it is possible that somewhere along this belt a peridotite of sufficient size to host a small nickel sulphide deposit could occur.

A.3.8 Wongi South

Wongi South in the Ora Banda area has been extensively explored but no nickel sulphides have been discovered. The serpentinites are peridotites, or olivine peridotites, based on their magnesium content, but are relatively low in nickel and high in chromium. They have relatively high Ni/NiP ratios, but these high values are more than offset by the low total nickel and high chromium contents (Table 44).

Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	Ni/Cr	Ni/NiP
3.08	525	1550	8	12.5	1.30	0.70	18.60	80	2700	1050	8.35	NA	62.5	160	0.57	2.95
2.61	725	1450	18	20	1.30	1.40	17.40	100	2800	1200	8.35	NA	57.5	130	0.51	2.00
3.31	325	1275	6	15	2.10	2.10	15.80	80	2500	1200	8.35	NA	37.5	120	0.51	3.92
2.83	675	1375	12	17.5	1.60	1.95	17.40	90	2800	1300	8.60	NA	55	130	0.49	2.03
3.03	700	1350	12	20	1.40	1.75	18.00	80	2800	1200	8.35	NA	57.5	130	0.48	1.92
NA	175	1625	nd	7.5	1.30	0.70	21.40	60	3000	950	7.60	NA	12.5	130	0.54	9.28
NA	125	1575	nd	7.5	1.30	0.60	19.60	60	2900	900	7.40	NA	10	130	0.54	12.50

Table 44. Geochemical analyses, canonical scores (B), Ni/Cr and Ni/NiP ratios of miscellaneous komatiite samples from Wongi South. Note that although the last two samples are peridotites and probably represent thick units, they are low in Ni and high in Cr (Ni/Cr ratios 0.54), and are thus considered to be Barren.

APPENDIX B

GEOLOGY AND GEOCHEMISTRY OF LEONORA-WILUNA NICKEL PROVINCE

The Leonora-Wiluna Nickel Province (Fig. 78) is the nickel rich eastern section of the Leonora-Wiluna greenstone belt, adjacent to and mainly west of the Keith Kilkenny lineament (Williams 1973). The Leonora-Wiluna greenstone belt is defined as the dominantly mafic sequence of rocks which extend northwestward from Leonora, includes Agnew and Perseverance, and terminates north of Wiluna. It ranges up to 30 km in width at Mt. Clifford and 55 km in width at Agnew. In both cases the substantial widening includes greenstone "arms" that extend southerly but appear to be less favorable for nickel sulphides.

The character of the Leonora-Wiluna Nickel Province is largely determined by major strike faults, particularly north of Weebo Bore. There faults cut the greenstones into blocks and usually form their boundaries with the surrounding granite and granite gneiss. Martin and Allchurch (1975), suggested that the preservation of the belt north of Perseverance is due to its being a complex graben. South of Weebo Bore the internal structure of the Leonora-Wiluna Nickel Province is dominated in part by strike faults, but also by basin-dome structures, probably caused by intrusive granites.

Two main rock associations have been recognized by Travis (1975):

1) Mafic-ultramafic sequence, chiefly tholeiitic basalts, ultramafic lenses and major ultramafic intrusions, and

2) Acid volcanic sequence, dominantly pyroclastics with subordinate massive units.

Chert horizons and magnetite rich quartzites occur throughout the layered successions.

Martin and Allchurch (1975), divide the greenstone belt into three sequences:

1) Lower basic volcanics with minor acid bands,

2) Sedimentary sequence, and

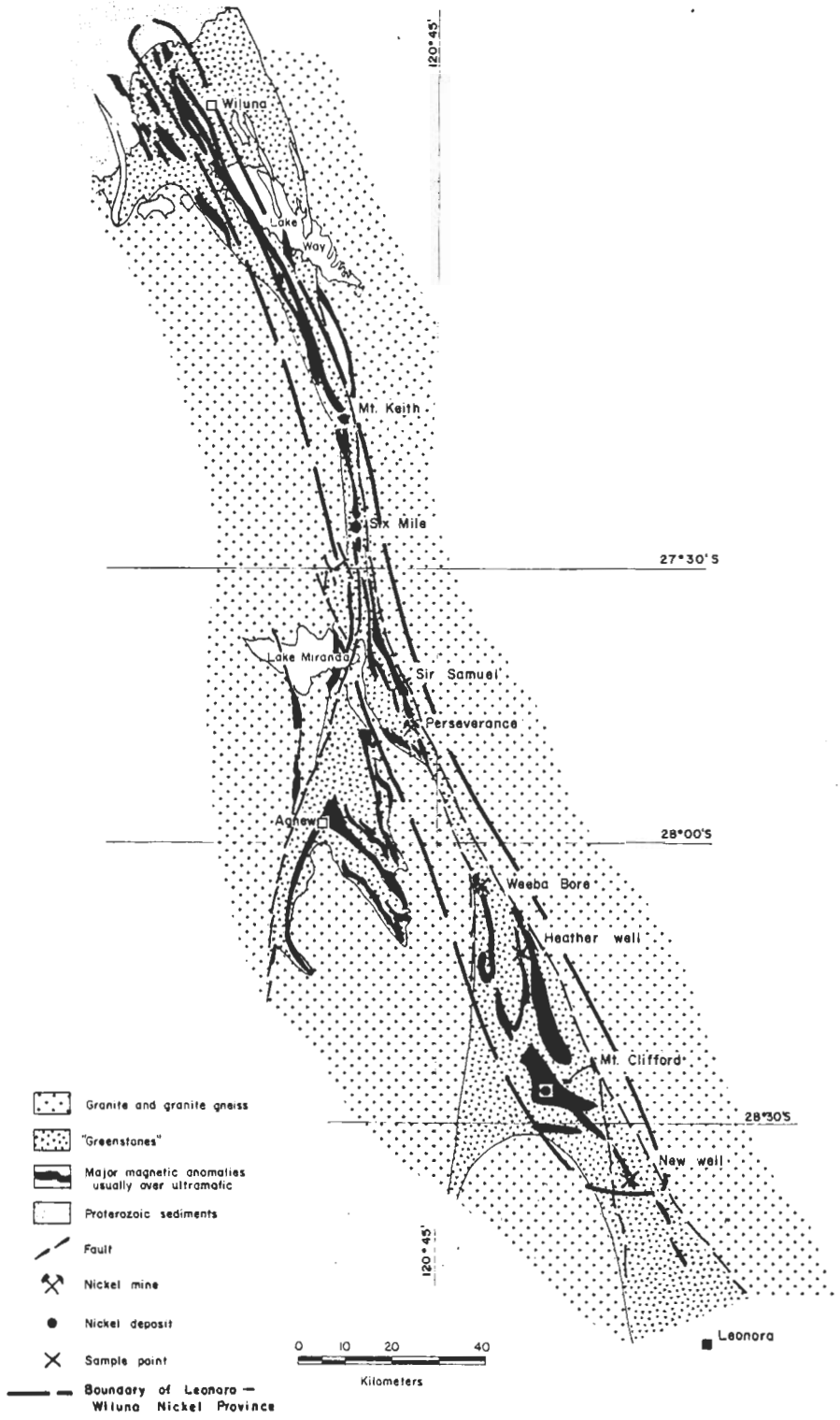

Fig. 78. Leonora-Wiluna greenstone belt showing location of nickel sulphide deposits and approximate extent of Leonora-Wiluna Nickel Province.

3) An upper unit of basic volcanics. Ultramafic rocks are present in both basic units.

The mafic rocks are metamorphosed tholeiites dominated by extrusive, fine-grained basalts with relic pillows, amygdales and associated breccias. Possibly penecontemporaneous bodies of dolerite form semi-concordant lenses. Two komatiite sequences are present. The Mt. Keith-Perseverance intrusive komatiite suite forms a semi-continuous unit over a strike length of 200 km. It contains disseminated nickel sulphides and is predominantly coarse-grained dunite, serpentinized dunite and talc carbonate rock. This komatiite suite consists of multiple penecontemporaneous, near vertical, sheet-like bodies which may have narrow peridotitic margins. A volcanic suite of komatiites which is not known to host nickel sulphides (Radford and Turner, 1975; Travis, 1975) is also well developed. Typical extrusive komatiite differentiation is well developed with olivine peridotite lower zones overlain by spinifex textured pyroxenite and pyroxene peridotite layers. High Mg basalts with well developed micro scale skeletal clinopyroxene and subordinate olivine occur near Wiluna.

Sedimentary intercalations of fine-grained chert, siltstone and sulphide-rich black shale or chert occur throughout the ultramafic-mafic associations. Sequences of shales, siltstones and arenites, with interbedded acid and intermediate volcanics also form separate major stratigraphic units. An extensive conglomerate horizon (the Jones Creek Conglomerate) has been described within these clastic sequences, and it has been suggested that this marks a major unconformity (Durney, 1972).

The Keith-Killkenny lineament (Williams 1974), forms a major boundary in the Eastern Goldfields Province, between the Kalgoorlie and Laverton subprovinces. Williams (1974) also speculates that this structure is the expression of a fundamental, mantle-tapping fracture that initiated and controlled the location of large intrusive ultramafic bodies and adjacent granite plutons.

Major occurrences of nickel sulphides within the Leonora-Wiluna Nickel Province occur at Mt. Keith, Six Mile and Perseverance (Fig. 79). Smaller occurrences are

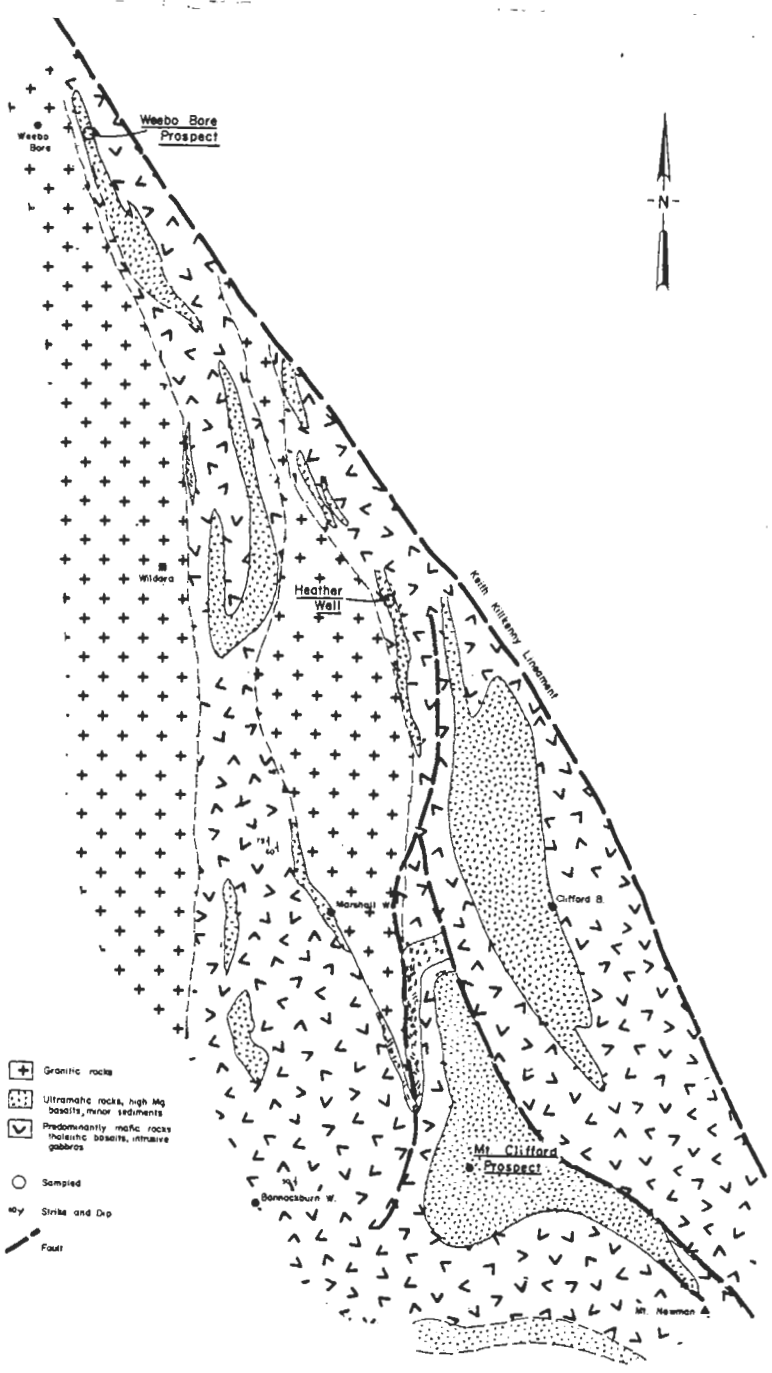

Fig. 79. Interpretive geology of the southern part of the Leonora-Wiluna Nickel Province showing location of Weebo Bore and Heather Well and Mt. Clifford nickel sulphide prospect.

known from Mt. Clifford, Weebo Bore and Sir Samuel. In addition, there are at lease six minor accumulations. The Perseverance deposit is at present being developed into a mine. The Leonora-Wiluna Nickel Province outranks all other nickel provinces in terms of contained nickel sulphide, but at the present time is below the Kalgoorlie-Norseman Nickel Province in economic importance. The nickel deposits are related to intrusive komatiite suites in contrast to the Kalgoorlie-Norseman Province where most, and perhaps all deposits are associated with volcanic komatiites. In addition the deposits are relatively low grade; have low or very low pyrrhotite to pentlandite ratios and thus a low proportion of massive sulphide and have high nickel to copper ratios (20 to 400:1).

Based on the spatial distribution and size of nickel sulphide deposits, a genetic relationship between the Keith-Killkenny lineament (and related structures) and the Leonora-Wiluna Nickel Province is indicated. There is a gradation from the northern end of the province, where low grade (0.6 percent Ni average grade - Mt. Keith) deposits only are known, through higher grade disseminated deposits with some massive sulphide (2.0 percent Ni average grade - Perseverance) at the center of the province, to volcanic (extrusive) suites at the southern end of the province (Mt. Clifford). The significance of these changes are speculative, but may imply that the Mt. Keith ultramafics represent deeper crustal levels, and that the crustal level (as represented by present day surface) becomes progressively shallower to the south. No fracture of similar importance to the Keith-Killkenny lineament has been defined in the Kalgoorlie-Norseman Nickel Province.

The present study used samples from mineralized komatiites at Sir Samuel and Weebo Bore and from barren komatiites at Heather Well (Fig. 79) and Mertondale. The geochemical results from each area will be discussed below - except for Heather Well, which was described earlier.

B.1 DESCRIPTIONS OF MAIN NICKEL SULPHIDE AREAS

B.1.1 Mt. Keith

Mt. Keith is large, low grade and uniformly disseminated, pentlandite mineral body, situated near the northern end of the Leonora-Wiluna Nickel Province. Indicated reserves are 263 million tons at 0.60 percent Ni (Sheppy and Burt 1975). The sulphide body is contained within a serpentinized dunite, which is a dyke-like intrusive body, intruding an intermediate to acid volcanogenic sequence (Fig. 80). The greenstone belt is narrow and averages 5 km in width. It consists of metavolcanic and metasedimentary rocks, bordered to both east and west by granitic rocks. The belt approximately coincides with the position of the Keith-Killkenny lineament. The volcanic rocks are dominated by a sequence of intermediate to acid tuffaceous rocks and subordinate flows. This sequence contains well defined, thin carbonaceous shales and cherts, which are commonly rich in sulphides.

At Mt. Keith the dunite dyke is composed predominantly of serpentinized dunite with narrow marginal peridotitic zones (Fig. 81). Mineralization is confined to the dunite core, and the peridotite margins are barren. Very fine-grained interstitial magnetite is common. The wall rocks strike north-south and dip 70-80 degrees west. They appear to have been isoclinally folded, but the folding and related cleavage has not significantly affected the dunite. The primary mineralization consists almost entirely of fine-grained pentlandite which is interstitial to serpentinized olivine grains. Minor pyrrhotite and millerite are present, and magnetite, chromite and stichtite occur as accessory minerals. Non-sulphide nickel approximates 0.11 percent for the assay range 0.4 to 0.8 percent. Nickel-cobalt ratio is 34:1 and nickel-copper ratio is 60:1. The Mt. Keith deposit is considered sub-economic at present.

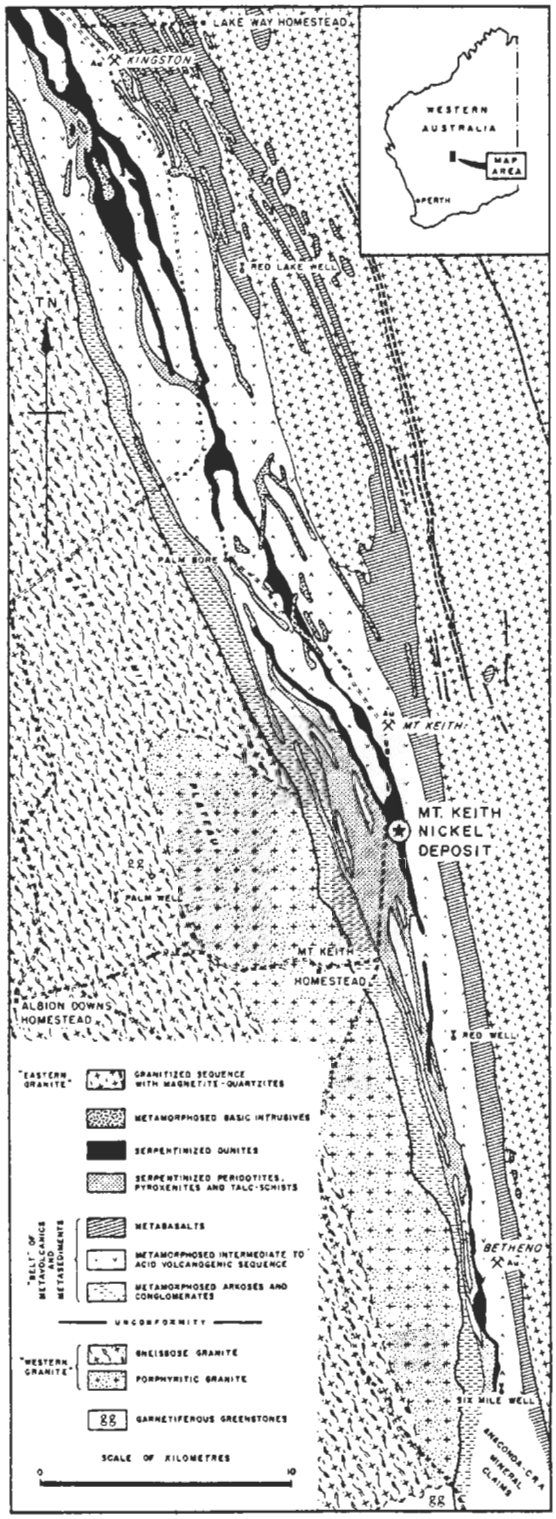

Fig. 80. Interpretive geology of the Mt. Keith region (from Sheppy and Burt, 1975). Note the linear, continuous nature of the dunites which is typical of the intrusive type of komatiite.

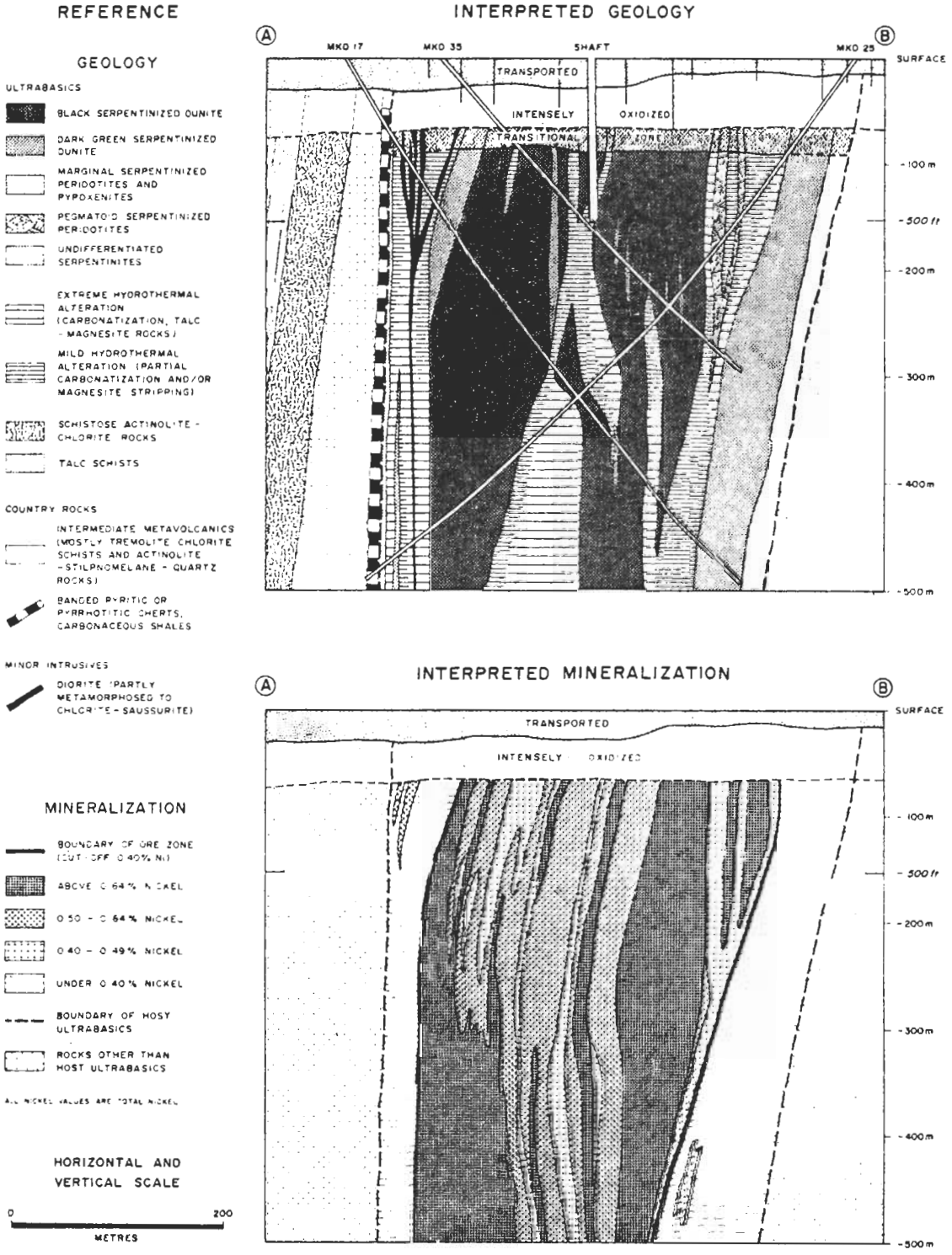

Fig. 81. Mt. Keith Nickel Deposit - Cross sections of geology and mineralization (from Sheppy and Burt, 1975). Mt. Keith is an example of nickel sulphide mineralization associated with intrusive type komatiites.

B.1.2 Six Mile Deposit

The Six Mile prospect is a relatively large, low grade, disseminated nickel sulphide deposit, apparently similar in character and origin to Mt. Keith (Turner & Ranford, 1975). The deposit has a strike length of 1500 m but mineralization reserves are not known.

Two komatiite suites are present; a stratigraphically controlled volcanic suite with spinifex textures, and a tectonically controlled intrusive suite, characterized by cumulate olivine textures. The intrusive suite contains the known mineralization. The regional structure (Fig. 82) is dominated by sub-parallel, strike slip faults, and cross cutting, tensional faults, both of which are probably related to the Keith-Killkenny lineament. The mineralized serpentinites are intruded into the tensional fault zones near their intersection with major strike slip faults (Turner and Ranford, 1975). Two types of serpentinite are present in the ultramafic host; a green serpentinite which is considered to have been derived from peridotite, and now consists of serpentine after olivine and pyroxene, and minor chlorite and tremolite; and a black serpentinite after dunite, composed entirely of serpentine pseudomorphs after olivine. Carbonatization has occurred on the margins and within certain zones in the ultramafic.

Sulphide mineralization occurs as disseminated grains and blebs within the black serpentinite and as fine grains and veinlets throughout the silicate gangue in the green serpentinite. Pentlandite is the dominant primary sulphide with variable, but lesser amounts of pyrrhotite, chalcopyrite and pyrite. Nickel copper ratio is 30:1.

B.1.3 Perseverance

The Perseverance nickel sulphide deposit is situated in the central part of the Leonora-Wiluna Nickel Province, adjacent to a major strike slip fault. Announced ore reserves are 45 million tonnes averaging 2 percent Ni

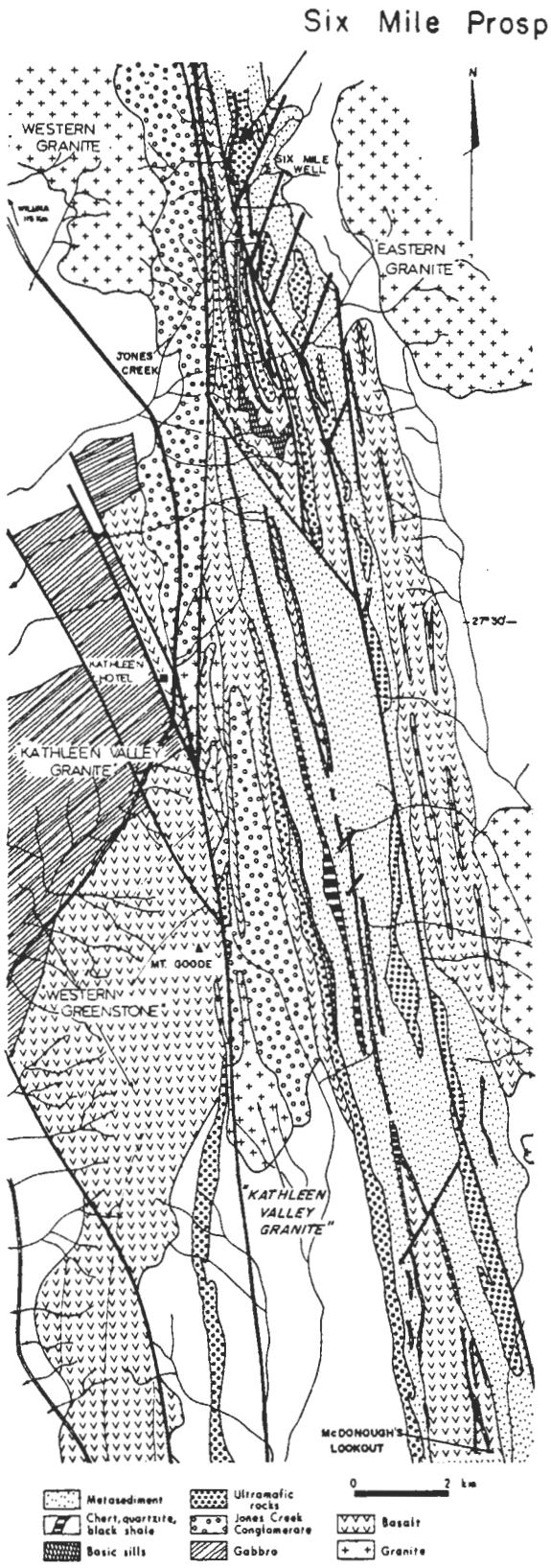

Fig. 82. Regional geology of Yakabindi Area (from Turner and Ranford, 1975). Nickel sulphides are associated with intrusive type komatiites at Six Mile prospect but not with volcanic type komatiites which are also present in the area.

at a 1 percent Ni cutoff (Martin and Allchurch, 1975). Nickel sulphides occur in a west dipping komatiitic intrusion, which is emplaced in steeply dipping quartz-feldspathic metasediments and amphibolites. The komatiite forms a lens shaped body 3 km long and ranges up to a maximum of 650 m wide. The eastern boundary of the lens is marked by a sheared and brecciated zone which is the approximate position of the Keith Killkenny lineament (Williams, 1974).

The komatiite lens consists of a central core of dunite surrounded by serpentinite (Fig. 83). The dunite is composed of equant, olivine crystals up to 100 mm in diameter, with interstitial crushed olivine. The serpentinite which was derived from the dunite, is mainly dark green lizardite with minor chlorite, magnetite and lath textured metamorphic olivine. The ultramafic lens has a prominent embayment on the western contact in which the sulphide mineralization is localized (Fig. 83). The embayment is faulted, and massive sulphide mineralization occurs in this fault zone where it cuts adjacent sediments. Disseminated sulphides occur as discrete "shoots" and three distinct shoots have been identified to date. The disseminated mineralization contains 15 to 20 percent sulphides and averages 1.9 percent Ni, at a 1 percent Ni cutoff. An envelope of lower grade sulphides surrounds the "shoots". Massive sulphides occur mainly as planar sheetlike bodies, apparently within fault zones, near or at the western contact. These massive sulphides are "breccia sulphides", and include wall rock fragments, and are considered to be remobilized primary sulphides. The massive sulphides have a pyrrhotite-pentlandite ratio of 4:1 and nickel-copper ratio of 25:1. Chrome spinel is erratic in occurrence but is concentrated in the massive sulphides relative to the disseminated sulphides and is virtually absent in the low grade envelope.

The disseminated ore within the unserpentinized dunite consists of pentlandite and pyrite with lesser pyrrhotite and minor chalcopyrite. In the low grade envelope the main sulphide is pentlandite with millerite and heazlewoodite. Within the

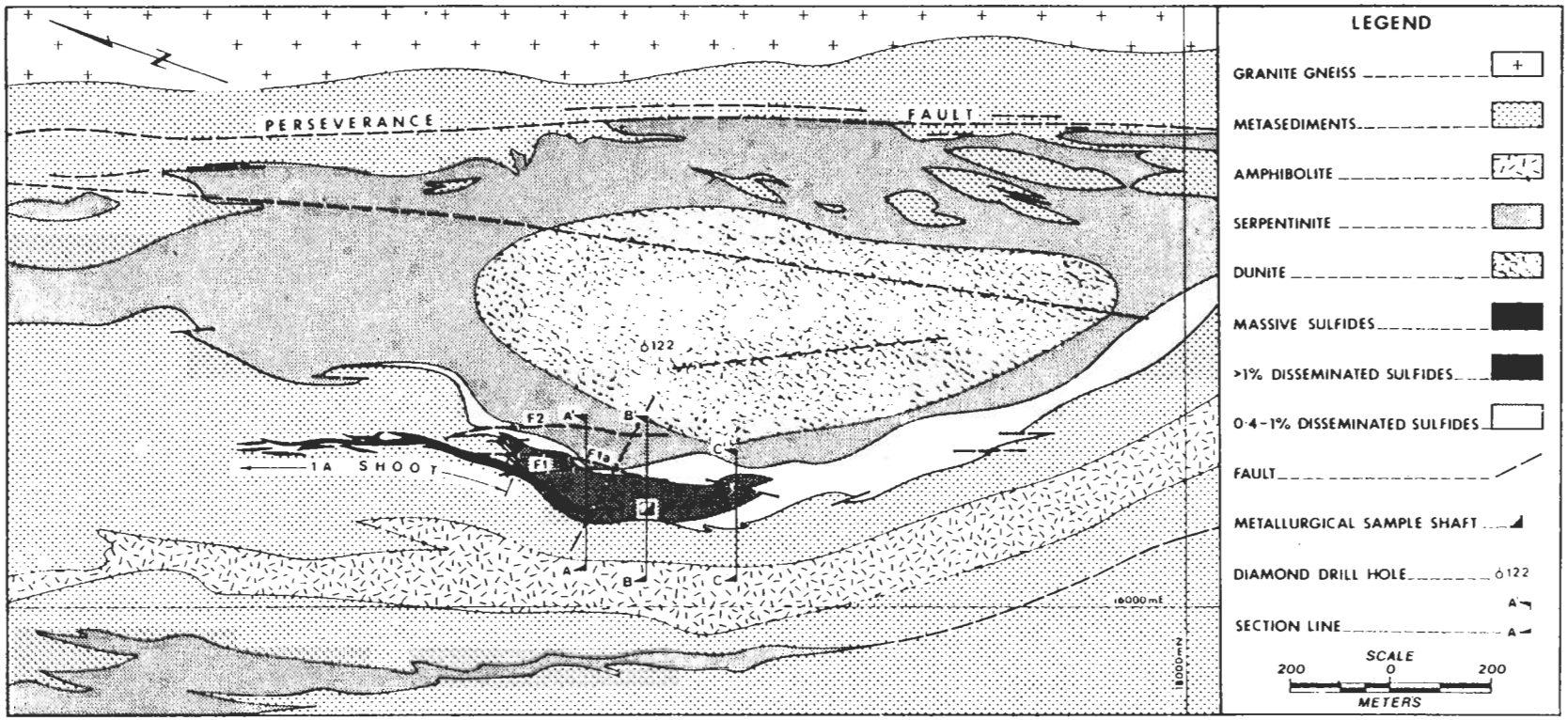

Fig. 83. Generalized geological map in the vicinity of Perserverance nickel deposit (from Nickel et al., 1977). Note the large remnant dunite core which has escaped serpentinisation. Remobilization of sulphides into the footwall rocks, probably during metamorphism, is also evident.

serpentinite, the sulphide assemblage consists of pyrrhotite and pentlandite with minor chalcopyrite and pyrite. A chrome valleriite is also present, apparently replacing chrome spinel (Nickel and Hudson, 1976). Primary pentlandite exhibits wide variations in nickel content, with the Ni/(Ni+Fe) ratio conforming to the composition of the sulphide assemblage in which it occurs. Nickel, et al. (1977), gives values ranging from 0.65 to 0.43. Magnetite occurs as discontinuous veinlets in the serpentine and as fracture fillings in the sulphides. The sulphides form interlocking grains, mainly interstitial to the serpentine pseudomorphs after olivine.

B.1.4 Mt. Clifford

Mt. Clifford is a small nickel sulphide deposit near the southern end of the Leonora-Wiluna Nickel Province, and is located 54 km north-northwest of Leonora (Fig. 79). A large, complex komatiite sequence extends from Mt. Clifford for 14 km to the northwest. The nickel deposit occurs within a large southwest bulge in this sequence, 7 km west-northwest of Mt. Clifford. Near the deposit, the rocks face north, and dip north at 30 to 50 degrees.

The ultramafic sequence has been divided by Travis (1975), into several components:

1) The basal ultramafic in the vicinity of the bulge is an intrusive, olivine rich ultramafic, termed olivinite by Travis (1975). It is 1000 m thick and is underlain by tholeiitic basalts. It is composed of lightly packed, serpentinized, equant to ellipsoidal olivines, 3-6 mm in diameter. It does not contain nickel sulphides but several sill-like gabbroic intrusives have been defined.

2) Overlying the olivinite is a serpentinized peridotite sequence, 100 to 140 m thick, which is the host to the nickel mineralization. The peridotites include a serpentinized olivine peridotite, composed of 80 to 90 percent olivine pseudomorphs set in a chlorite matrix; and serpentinized peridotites which contain 40 to 50 percent olivine pseudomorphs and exhibit a wide range of skeletal and elongate olivine pseudomorphs.

3) The third unit which overlies the peridotites, is a fragmented ultramafic-sedimentary unit, 10 to 30 m thick and composed of ultramafic fragments in a black matrix.

4) Overlying the fragmental sedimentary unit is a massive serpentine-amphibole-chlorite rock, 30 m thick.

5) A second fragmental ultramafic-sedimentary unit overlies the massive serpentine-amphibole-chlorite rock.

6) The final component to the sequence is a thick (500 to 1500 m) pile of ultramafic lavas as thin units. These flows average 2 to 5 m in width, contain chilled and fractured flow tops, spinifex zones and equant olivine zones.

The nickel mineralization occurs as disseminated sulphides in the equant olivine peridotite (2 above). The largest lens of sulphides defined is 250 m long and up to 10 m thick. The sulphides are nickel rich and consist of millerite, godlevskite, heazlewoodite and pentlandite with varying, but generally lesser amounts of pyrrhotite and pyrite.

B.2 GEOLOGY AND GEOCHEMISTRY OF AREAS SAMPLED

B.2.1 Weebo Bore

The Weebo Bore nickel prospect is situated 240 km north-northwest of Kalgoorlie within the Leonora-Wiluna Nickel Province and adjacent to the Keith-Killkenny lineament (Fig. 79).

The greenstone belt at Weebo Bore is only 900 m wide, and is flanked by schistose granite to the east and west. The stratigraphic sequence within the greenstone belt, according to Legge (1975), is as follows (Fig. 84):

1) The western and hangingwall rocks are fine to coarse-grained amphibolites which have been extensively intruded by acid porphyry dykes. Disseminated grains and narrow veins of pyrite, pyrrhotite and chalcopyrite occur within the amphibolites, but total sulphide content is seldom greater than 1 percent.

2) The mineralized komatiite lens is an elongate body which plunges north, and dips steeply west. It has a maximum width of 80 m and a length in excess of 300 m. The ultramafic can be divided into a core of weakly mineralized, serpentinized peridotite and an envelope of strongly mineralized, serpentinized dunite.

3) Underlying, and in sharp contact with the ultramafic, is a lithologically complex suite of fine-grained leucocratic schists which include metasediments, volcanics, and ultramafics.

The mineralization between depths of 135 and 280 m consists of pyrite, pentlandite, millerite, and chalcopyrite. Between 70 m and 135 m it consists of pyrrhotite and pentlandite in approximately equivalent amounts (Legge, 1975). Visible sulphides were present in most samples used in this study (Table 45). The widespread disseminated nature of the occurrence is illustrated by the generally high Ni and Ni/P values (Table 45) throughout the entire width of ultramafics sampled. The host rock is chemically homogeneous olivine peridotite in composition, and contains higher chromium values than most other mineralized komatiites in this study.

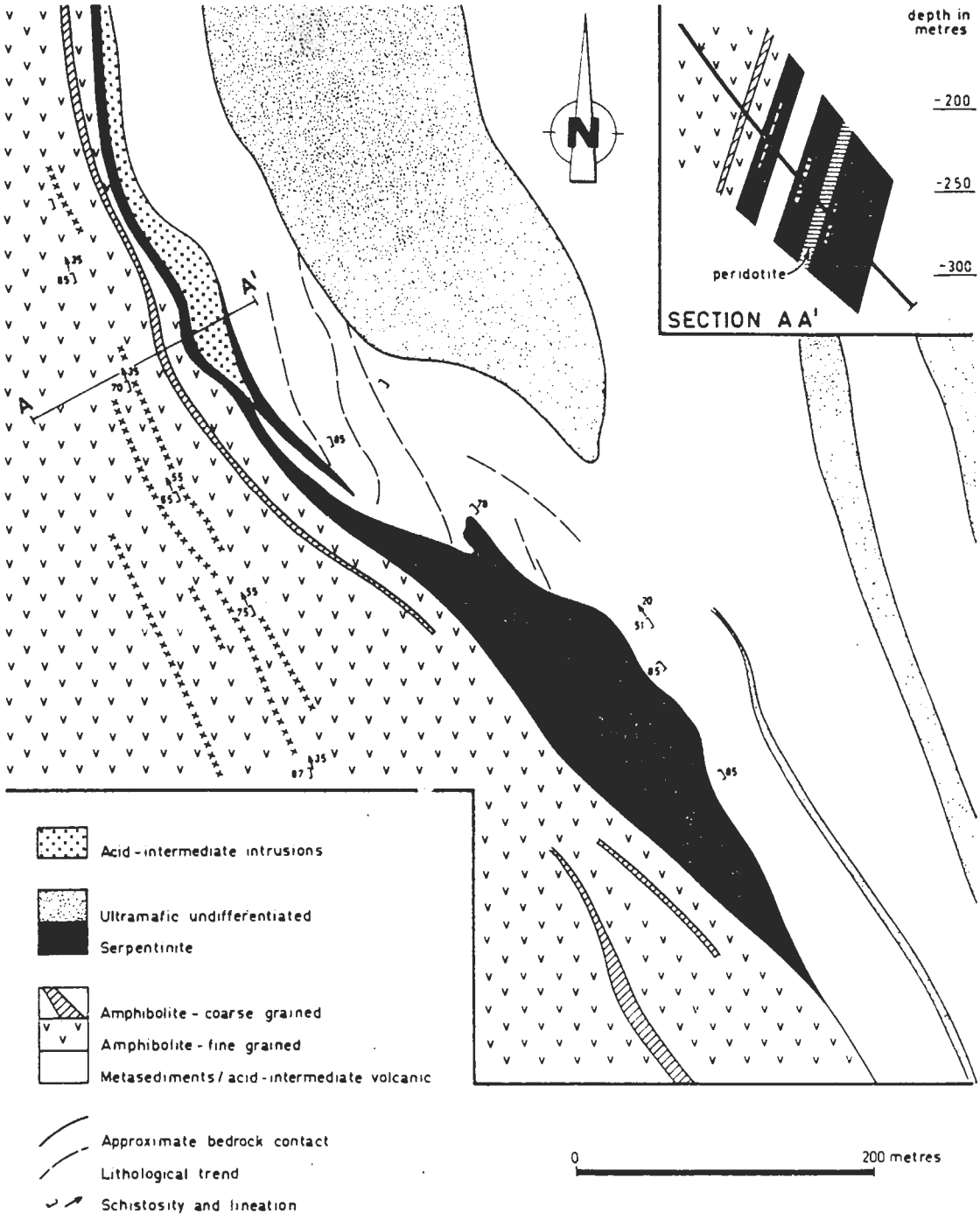

Fig. 84. Geological bedrock map and cross section, Weebo Bore nickel deposit (from Legge, 1975).

Depth Meters	Depth Feet	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co
191	627	ND	1.26%	1.50%	352	370	0.25	0.20	20.00	60	2050	800	10.00	0.04	113	340
	640	1.37	3400	4000	54	75	0.86	0.15	21.70	110	2600	1400	5.80	0.14	75	150
	700	0.72	6800	7800	276	305	0.58	0.15	22.80	60	1400	700	7.20	0.07	103	210
	715	ND	7800	8800	530	650	0.43	0.15	21.70	50	1000	500	7.20	0.07	100	220
	735	1.34	3600	4200	130	160	1.50	0.10	20.50	80	3000	1400	7.80	0.20	85	140
	760	1.64	2300	2650	80	95	1.40	0.15	20.00	100	2400	1600	6.90	0.15	50	135
	790	ND	1.10%	1.19%	535	600	0.25	0.45	19.40	50	1100	850	8.60	0.04	50	230
	835	1.00	5400	6200	172	210	0.47	0.30	22.20	60	1400	800	5.80	0.07	65	165
	860	1.06	5000	5700	254	300	0.46	0.10	21.70	40	800	500	6.10	0.07	40	190
	895	ND	9400	1.06%	440	500	0.39	0.15	20.50	50	1700	700	7.80	0.04	60	210
	920	1.89	6500	7400	200	238	0.68	0.20	20.50	90	2950	900	8.00	0.07	85	260
	950	1.39	5200	5800	268	325	0.64	0.20	21.10	60	1800	800	6.90	0.07	55	170
297	975	0.66	6600	7200	164	203	0.79	0.30	21.10	120	1900	1200	6.40	0.07	130	210
288	880	1.14	6200	6700	236	250	0.67	0.20	20.50	40	1200	700	7.80	0.07	40	185
	975	2.18	175	250	260	273	6.40	5.05	4.50	100	250	1400	7.20	1.14	20	80
	1015	ND	1.37%	1.70%	800	800	0.47	0.20	19.40	90	1900	750	8.80	0.07	95	285
	1060	2.33	1400	2200	8	15	1.95	0.35	20.50	70	2550	2000	6.60	0.23	62	140
	1114	1.58	6700	7800	148	160	0.67	0.20	18.80	70	2300	1200	7.80	0.13	62	225
	1165	ND	8200	1.00%	450	450	0.91	0.15	18.80	60	1700	850	7.80	0.09	75	230
372	1220	1.15	4000	4500	158	165	0.89	0.35	20.00	140	2900	1300	7.80	0.10	80	160

Table 45. Geochemical analyses and canonical scores (B), for komatiite samples from a Mineralized, intrusive komatiite sequence at Weebo Bore. Most samples contain significant nickel sulphides. Note that even in samples with up to 1.5% Ni, Mg, Al and Ca content is approximately the same as in samples which contain little or no sulphide. In addition, Cr content is also apparently unchanged, and Fe content is only slightly increased.

Iron contents are also relatively high, but TiO_2 values are low; Cu to Ni ratio is approximately 30. The two ultramafic types described by Legge (1975) are not reflected in this restricted sample population.

B.2.2 Sir Samuel

Sir Samuel is a small nickel sulphide occurrence 18 km north of Perseverance (Fig. 78), within the central sector of the Leonora-Wiluna Nickel Province. The Sir Samuel komatiite sequence is approximately equivalent in stratigraphic position to the Perseverance ultramafic. These komatiites are of intrusive origin and are probably genetically related to the Keith-Killkenny Lineament.

Eleven samples were selected from five drill holes. Petrographic examination revealed that most samples belonged to the serpentine-talc-tremolite-chlorite suite. Two samples contained remnant olivine textures and could be classified as olivine peridotites or dunites. The samples represent at least three separate komatiite intrusives.

The geochemical results shown in Table 46 indicate that the komatiites are mainly cumulate olivine rocks and relatively high in Ni and NiP. Two samples, however, differ and contain high chromium contents. There are insufficient samples to draw any significant conclusions other than as would be expected; most of the samples have a moderate to high mineralization coefficient.

B.2.3 Mertondale (24)

Nineteen samples were obtained from an ultramafic at Mertondale near the southern end of the Leonora-Wiluna Nickel Province. The samples were spot core, from four (4) diamond core holes, which tested a komatiite sequence of unknown dimensions.

The komatiites are all serpentinized to varying degrees, and the majority of samples were originally olivine peridotites with between 50 and 75 percent olivine. Some talc-carbonate and chlorite rich samples are present but no spinifex textures were noted. Fresh pyroxene occurs in several samples. The

Sample	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoS	Co	S	Ni/Cr	Ni/NiP
1	3.15	900	1625	2	2	1.25	1.10	18.60	70	4100	1200	7.10	0.13	97	160	0.075	0.40	1.80
2	2.72	825	1375	2	5	1.00	5.80	16.60	60	1300	1500	6.10	0.10	50	130	0.04	1.06	1.67
3	0.43	2150	2700	40	45	2.05	1.00	18.60	60	850	850	4.80	0.17	70	110	0.21	3.18	1.26
4	1.36	1750	2550	2	2	1.00	0.09	21.30	20	1550	800	5.00	0.05	57	90	0.36	1.65	1.46
5	1.58	3350	5200	88	95	0.40	0.03	21.80	20	1150	200	5.20	0.04	135	180	0.52	4.52	1.55
6	2.07	1875	3150	2	5	0.83	1.30	20.00	20	1250	900	6.20	0.10	95	130	0.18	2.52	1.68
7	1.43	1150	1950	48	55	0.33	0.03	23.00	20	1000	700	4.70	0.02	42	70	0.32	1.95	1.70
8	1.76	1625	2350	2	2	1.35	0.71	20.50	20	1150	900	4.60	0.10	72	120	0.10	2.04	1.45
9	3.80	1375	1950	32	35	0.84	0.72	20.00	70	4800	1750	6.70	0.07	157	200	0.19	0.41	1.42

Table 46. Geochemical analyses and canonical scores (B) Ni/Cr and Ni/NiP ratios for 9 samples from a Mineralized, intrusive komatiite at Sir Samuel. Samples 3 to 8 inclusive are considered to be typical of a mineralized intrusive sequence. Lack of geologic control precludes comment on samples 1 and 9, which are high in Cr.

petrography and chemistry of the Mertondale komatiites indicate that they are probably part of a volcanic suite or an extremely well differentiated intrusive.

No nickel sulphides are known in this area, and for the statistical analysis, Mertondale was designated as Barren. The discriminant analysis tends to confirm this assumption. The geochemical results (Table 47) show that in general the sequence is extremely low in S and NiP, and high in Cr. There are exceptions such as the upper section of hole D which is an olivine peridotite with low Cr, but also low NiP. The sampling is not detailed enough to comment on these discrepancies.

The statistical analysis and geochemical results indicate that this komatiite sequence is unlikely to host nickel sulphides in the immediate vicinity of the drill holes sampled but the sequence does have some mineralization characteristics.

Hole No.	Depth	Canonical Score	NiP	Ni	CuP	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	CoP	Co	S
A	87	2.35	100	2250	8	14	1.45	0.84	20.80	80	1150	950	6.50	13	140	0.010
	110	ND	190	800	4	11	0.91	12.10	15.60	40	900	3200	5.20	20	60	0.010
	126	3.29	325	1250	16	23	1.85	9.10	14.45	70	2000	1650	5.55	28	100	0.020
	131	2.99	575	1825	6	9	2.60	2.60	15.60	80	3500	900	6.40	48	120	0.040
	136	3.29	250	1660	8	14	3.65	7.60	9.70	80	1550	1300	6.00	20	100	0.020
B	67	3.98	75	1950	2	12	2.60	2.12	14.70	90	4100	350	6.90	8	80	0.005
	72	3.77	165	1650	12	29	2.20	1.50	15.90	80	3450	900	6.40	18	100	0.005
C	76	ND	100	1050	4	20	0.99	10.60	17.55	50	600	1750	3.40	8	100	0.025
	91	2.83	200	2100	8	15	2.00	1.91	20.00	70	1200	1200	6.80	8	140	0.010
	107	ND	40	500	2	7	0.85	13.10	14.65	50	650	2300	4.00	8	60	0.005
D	58	3.59	215	2375	2	42	1.35	0.98	20.50	70	1000	800	5.50	10	140	0.010
	73	2.43	250	2150	12	23	1.35	1.20	20.50	80	1050	1050	6.05	13	140	0.020
	98	2.36	425	2075	18	24	1.70	1.91	20.00	70	1350	1100	6.00	13	120	0.045
	ND	ND	425	725	44	47	1.95	11.10	10.50	70	2900	1500	6.90	13	100	0.020
	ND	ND	50	600	10	12	2.05	13.50	9.50	150	2900	1900	6.80	5	100	0.020
	ND	3.91	200	1625	14	19	1.80	2.40	15.40	70	2500	1650	10.10	25	170	0.025
	ND	3.73	275	1725	24	25	2.20	3.00	15.00	70	2550	1600	9.00	28	170	0.025
	ND	3.81	315	1150	60	66	1.55	7.45	11.80	80	2150	2250	9.40	48	150	0.045
	ND	3.37	400	1625	76	75	1.95	1.75	14.30	80	2550	1500	10.20	53	170	0.045

Table 47. Geochemical results and canonical scores (B) for core samples from four drill holes at Mertondale. The samples probably represent both thick and thin units and can be regarded as Barren on the basis of combined NiP, Ni and Cr results. Note that although the peridotite unit in hold D (plus 20% Mg) has low Cr, canonical scores, on the basis of very low NiP and CoP suggest the thick unit is Barren.

APPENDIX C

GEOLOGY AND GEOCHEMISTRY OF THE WINDARRA NICKEL PROVINCE

The Windarra Nickel Province is situated 240 to 260 km north-northeast of Kalgoorlie in the northeastern section of the Wiluna-Norseman belt (Gee, 1975). Two nickel mines, Windarra and Windarra South, have been developed and nickel sulphides are known at several other localities in the province.

The Windarra Nickel Province is a wedge-shaped zone of north to northwesterly trending metavolcanics and metasediments surrounded by intrusive granite plutons and granite gneiss (Fig. 16). A prominant banded iron formation forms the western boundary of the greenstone belt over much of its length. Remnants of mafic and ultramafic rocks extend to the west of Windarra South and trace amounts of nickel sulphides have been reported in a small ultramafic zenolith about 8 km west of Windarra South (Roberts, 1975).

The stratigraphy within the greenstone belt can be divided into three main units:

1. The basal unit is a banded iron formation which varies from zero to 150 m in thickness. This banded iron represents metamorphosed (amphibolite facies) carbonate and sulphide facies iron formation. It consists of quartz-amphibole-magnetite and quartz-amphibole-sulphide rocks with minor intercalated chert and biotite schist. Ultramafic rocks are known in some localities underlying the banded iron but in most cases the banded iron is in irregular contact with granite gneiss.
2. Overlying the banded iron unit is a complex komatiite ultramafic sequence which is host to nickel sulphide mineralization. It varies from a few meters to 700 m in thickness, and has been extensively metamorphosed and altered. Primary silicate textures are rare. The geochemical studies at Windarra South indicate that the ultramafic is a multi-layered sequence of komatiites and can be classified as a volcanic suite. It is similar to

other komatiite volcanic suites with relatively thick peridotite and olivine units (thick units) at the base, overlain by a multitude of thin, less mag sium rich units (thin units). This conflicts with the origin proposed by Roberts (1975).

3. Overlying the komatiite sequence is a thick (plus 400 m) sequence of metamorphosed basalts. These basalts are now sheared and massive amphibolites with rare intercalated sedimentary and sulphide rich beds.

Samples were obtained from two areas - Windarra and Windarra South. Windarra will be described below and Windarra South was discussed earlier in this thesis.

C.1 GEOLOGY AND GEOCHEMISTRY OF AREAS SAMPLED

C.1.1 Windarra

The Windarra nickel sulphide mine is medium sized and total volume of sulphides above 0.5% Ni at June 1973 was 11.3 m tons at 1.46% Ni and 0.14% Cu (Roberts, 1975). Regional metamorphism has obliterated most original textural features within the komatiites but the writer considers that these deposits fall within the volcanic suite.

Nickel sulphides at Windarra occur as predominantly north-south striking, sheet-like, near vertical lenses. These lenses are apparently conformable and occupy a similar stratigraphic position over a strike length of 1,520 m. Ore widths range from less than 3 m to 13 m and average 5 m (Roberts, 1975). The stratigraphy from east to west can be summarized as follows (Roberts, 1975): Granite and granite gneiss; metabasalts (both tholeitic and olivine rich types) with some intercalated ultramafic rocks; komatiite unit with one or more intercalated sulphide-rich sediment horizon and containing nickel sulphides in at least two stratigraphic horizons; banded iron formation; granite and gneiss.

The western granite is a strongly lineated, weakly foliated, porphyritic quartz microcline-andesine, biotite granite. It is overlain by a banded iron formation which varies from 80 to 150 m thick. According to Roberts (1975), this banded iron is a metamorphic rock derived from an original rock sequence which consisted of banded chert-siderite, chert-siderite-pyrite, chert pyrite and massive pyrite rocks with intercalated pelitic horizons. At Windarra, the banded iron contains a higher percentage of sulphides than along strike, both north and south.

The komatiite sequence is inhomogeneous and has been divided into two sequences by Roberts (1975): a main sequence which contains the nickel mineralization and consists of serpentine-talc-carbonate lithologies; and a footwall sequence, devoid of sulphides which is mainly talc, chlorite carbonate

rocks (Fig. 86). All ultramafic rocks are metamorphosed, metasomatized and devoid of primary mineralogy. The main ultramafic sequence ranges from 90 to 150 m and the footwall ultramafic from 3 to 45 m in thickness. At ultramafic metasediment contacts, biotite-chlorite-actinolite-tremolite assemblages occur and according to Roberts (1975) are of contact reaction origin. Mineralogical and chemical studies suggest that the bulk of the komatiite sequence consists of a number of thin units but deformation has destroyed any visual evidence of a consistent pattern. Serpentinite occurs within the lower part of the main ultramafic and consists of coarse interlocking antigorite blades accompanied by varying amounts of talc and magnesite (often as veinlets). Fine to medium grained actinolite-tremolite-chlorite schist occurs throughout the ultramafic and may contain minor talc, carbonate and opaque minerals (Roberts, 1975). Opaque minerals within the ultramafic (not within ore) include magnetite, chromite and pyrite. The chromite occurs only as cores of magnetite grains. The most olivine rich section of the ultramafic sequence appears to have been the zone immediately above the lowermost internal metasedimentary (banded iron) unit (Fig. 86) which corresponds to the basal part of the main ultramafic (as referred to in this text). The textures and mineralogy of the ultramafic sequence indicate amphibolite facies grade regional metamorphism.

Overlying the komatiites are a thick sequence of both tholeiitic and olivine rich metabasalts with interlayered and interfingering narrow ultramafic units (Roberts, 1975). These rocks are now schistose and dark green amphibolites and consist mainly of hornblende, quartz and plagioclase with minor chlorite, carbonate, sphene, granet, biotite and opaques. Plagioclase is sericitized and often altered to epidote or clinozoisite. Some metabasalts are magnesium rich and can be classified as high Mg basalts (Roberts, 1975).

Seven ore shoots have been defined at Windarra (Roberts, 1975). The primary ore consists of massive, breccia and disseminated sulphide-oxide ore with disseminated mineralization most abundant. The bulk of the ore occurs at or near

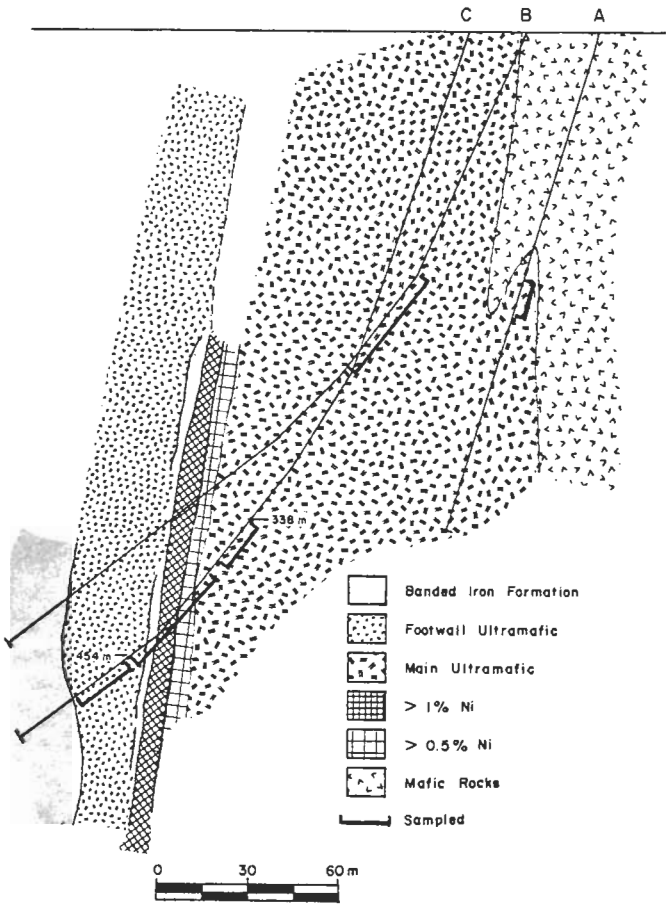

Fig. 85. Diagrammatic cross section of D shoot area, Windarra, showing relationship of samples to mineralization, and main and footwall ultramafics.

the contact of the main ultramafic sequence with a thin but persistent sulphide rich sedimentary unit, in proximity to but separate from the main banded iron formation. Additional ore occurs higher in the main ultramafic sequence associated with a further sulphide rich sedimentary horizon. Roberts (1975) states that the footwall ultramafic is apparently barren but one sample from this study recorded 0.84% Ni.

Average disseminated ore contains 15-25% sulphide in an ultramafic gangue. Ore grade varies up to 5% Ni and highest grades normally occur 5 to 10 m above the sulphide sediment horizon. The sulphides consist of pentlandite and pyrrhotite in approximately equal amounts.

Massive sulphides with dominant pyrrhotite and subordinate pyrite, pentlandite and chalcopyrite occur at the base of the main ultramafic sequence near its contact with the thin sulphide sediment layer. Pyrrhotite-pentlandite ratios may be as high as 20:1. Nickel to copper ratios of both massive and disseminated sulphides are approximately 12:1.

Breccia ore and banded iron formation ore are intimately associated with the underlying sedimentary unit. The banded iron formation ore is usually low grade but may exceed 1% Ni in restricted areas (Roberts, 1975). Whether massive or breccia ores are developed adjacent to ultramafic-metasediment contact depends on the petrology of the sulphide sediment. The sulphide sediments contain three main mineral assemblages: quartz-pyrrhotite-pyrite-actinolite-biotite; banded to foliated actinolite-biotite-chlorite and talc-chlorite-tremolite; banded quartz-actinolite-hornblende, albite-actinolite-hornblende, biotite rocks with pyrite or pyrrhotite. Breccia and massive ores are only developed adjacent to the first assemblage (Roberts, 1975).

Seventy-six samples of ultramafic rock were obtained from Windarra but ultimately only 57 were used in the statistical analysis. The others were rejected mainly because of high nickel content. Thirteen samples were miscellaneous rock samples from underground exposures; 12 samples were spot core samples

and the remainder were drill core assay pulps. The drill hole samples represent the ultramafic in the D shoot (Roberts, 1975) area and the rock samples represent the E shoot and Shirley shoot areas. Samples from holes A, B, and C (Table 48) except for the part of hole C below 446 m, each represent approximately 1.5 m of ultramafic. In hole A the sample centers are spaced at 3.1 m intervals; in holes B and C at 4.5 m intervals.

47% of the samples were classified as Mineralized in discriminant analysis A and 53% in analysis B (Table 4). The poor classification is a direct result of the relatively low mean Ni/Cr ratio of 0.9 (Table 4). In all determinations other than Cr, the mean Windarra values approximate the mean values for all mineralized groups (Table 3). Detailed interpretation of Windarra geochemical results (Table 48) does not yield any reasonable explanation for the high Cr content of these komatiites compared to similar "volcanic" sulphide hosts at Windarra South, Kambalda and elsewhere. All other aspects of the geochemical results are favorable for the presence of nickel sulphides. These include low Ni/NiP ratios (mean 1.9), low Fe and Mn and the presence of peridotite and olivine peridotite komatiites.

The results for Section 466 to 532 m in hole C (Table 48) represent the footwall or western ultramafic. This ultramafic appears to be chemically similar to the main ultramafic sequence except for a slightly lower Ni and Mg values. Although Roberts (1975) states that this ultramafic does not contain sulphides, the presence of significant sulphur is indicated by the moderate NiP values and high Ni to NiP ratios.

The Windarra geochemistry is particularly significant in that it is the only mineralized komatiite sequence which does not have a signature completely distinctive from barren ultramafic sequences. This may infer a somewhat different or modified origin for the Windarra sulphides. One possible solution is that metamorphic processes have been important at Windarra with significant local transfer of sulphur from the banded iron formation to the ultramafic. If

Hole No.	Depth Meters	Depth Feet	Canonical Score	NiP	Ni	Cup	Cu	Al	Ca	Mg	Zn	Cr	Mn	Fe	TiO_2	CoP	Co	Ni/Cr	Ni/NiP
A	157	515	3.66	150	1050	41	40	2.60	6.20	11.10	100	2500	1550	7.90	0.63	18	105	0.42	7.00
		525	2.76	913	1850	73	70	0.68	7.30	13.00	60	2000	1000	4.40	0.08	55	95	0.93	2.02
		535	3.73	138	1225	19	38	2.75	2.12	12.60	100	2650	1050	6.60	0.38	20	105	0.46	8.87
		540	3.61	100	1075	50	48	3.55	4.15	11.90	110	2650	1350	7.70	0.44	18	105	0.40	10.75
		545	3.73	38	850	4	13	3.70	5.35	11.50	230	2300	1450	7.70	0.44	8	95	0.37	22.30
		550	2.75	163	875	9	13	3.40	4.40	11.90	240	2250	1350	7.30	0.46	15	100	0.39	5.36
	171	560	3.10	213	1200	21	28	3.70	2.44	13.00	150	2800	1050	7.30	0.50	23	115	0.43	5.63
B	168	550	3.61	238	1800	30	43	1.80	6.30	11.90	160	2200	2000	10.10	0.06	120	275	0.82	7.56
		565	3.74	775	2350	18	20	0.49	3.41	15.40	40	2850	1950	3.50	0.05	58	115	0.82	3.03
		580	2.38	1325	3125	25	28	0.53	0.07	18.20	50	2200	950	4.90	0.05	83	150	1.42	2.35
		595	3.06	913	2350	16	15	0.52	0.64	16.00	50	3600	850	4.60	0.05	58	105	0.65	2.57
		610	2.81	1075	2300	40	45	0.48	0.07	18.00	50	3350	650	4.90	0.05	58	105	0.69	2.14
		625	2.42	1163	2275	18	18	0.49	0.03	18.60	50	2750	750	4.40	0.05	60	110	0.83	1.96
		640	2.61	1525	2500	24	23	0.48	0.10	17.00	50	2800	600	4.60	0.05	68	125	0.89	1.64
		655	2.69	750	1950	13	15	0.51	0.23	17.00	50	2650	400	4.60	0.06	43	95	0.73	2.60
		670	1.59	4200	7500	153	170	1.20	0.43	17.00	40	1250	1050	5.80	0.16	140	250	6.00	1.79
		685	1.68	1900	3375	48	58	1.05	1.82	16.60	40	1200	950	5.60	0.08	80	135	2.81	1.78
		700	1.36	1900	2850	40	33	1.00	0.43	18.20	40	1150	950	4.60	0.11	70	115	2.48	1.50
		715	2.67	1138	2400	20	25	0.56	0.05	17.80	50	3150	600	4.40	0.06	53	105	0.76	2.11
		730	2.35	638	1925	18	18	0.68	0.02	17.40	60	3300	400	4.60	0.05	38	85	0.58	3.01
		745	2.76	1675	3125	29	28	0.58	0.80	17.40	60	3850	900	4.90	0.03	73	125	0.81	1.86
		760	2.67	1275	2525	21	28	0.65	0.07	18.00	60	3400	750	5.60	0.03	65	125	0.74	1.98
		775	3.12	825	1975	15	23	0.56	2.00	17.40	50	3000	1050	6.60	0.03	68	110	0.66	2.39
	241	790	2.96	1000	2500	19	23	0.61	0.55	17.80	50	3800	700	6.90	0.03	58	115	0.66	2.50
C	338	1110	2.29	1713	2250	66	60	1.05	0.22	21.00	50	3400	450	6.20	0.14	75	110	0.66	1.31
		1125	2.29	2900	3575	94	108	1.07	0.12	19.20	50	3550	400	5.20	0.14	103	135	1.00	1.23
		1140	2.10	2000	2750	69	63	1.03	1.80	18.80	60	3550	700	6.30	0.11	70	100	0.77	1.38
		1155	2.66	3950	5500	84	133	0.71	0.09	18.30	70	3650	450	5.70	0.08	158	240	1.51	1.39
		1170	2.67	1900	3425	69	113	0.61	0.09	19.00	50	3000	350	6.40	0.11	88	155	1.14	1.80
		1185	2.37	2400	3625	81	95	0.81	0.09	21.00	50	3150	350	6.80	0.11	110	170	1.15	1.51
		1200	2.54	1438	2700	46	55	0.76	0.10	21.20	50	3450	550	6.50	0.07	85	130	0.78	1.88
	370	1215	2.67	525	1550	21	28	0.56	0.09	21.20	50	2750	750	6.50	0.12	43	90	0.56	2.95
	382	1250	2.35	2425	3775	64	75	0.97	0.30	18.20	90	3250	700	4.50	0.08	115	175	1.16	1.54
		1265	2.76	1363	2925	40	43	0.94	0.95	17.40	100	3850	1100	5.50	0.12	78	155	0.77	2.16
		1280	2.09	2575	3550	114	148	0.75	2.06	17.00	70	2000	950	5.00	0.11	93	145	1.78	1.37
		1295	ND	5000	6400	500	600	1.00	0.50	15.40	100	2050	1100	5.60	0.14	150	200	3.12	1.28
		1310	ND	5900	7100	563	650	1.05	0.43	15.40	110	2250	1250	5.80	0.14	140	190	ND	ND
		1325	ND	6900	7900	550	750	1.05	0.40	15.80	110	2150	1350	6.40	0.14	125	185	ND	ND
		1340	ND	6150	7100	600	675	1.05	0.06	15.80	100	1650	1250	5.80	0.16	128	175	ND	ND
		1355	ND	7150	7600	488	625	1.05	0.06	16.60	100	1850	1300	6.40	0.16	128	180	ND	ND
		1370	ND	1.26%	1.32%	700	950	1.05	0.21	16.20	70	1950	1000	7.20	0.16	180	250	ND	ND
		1385	ND	2.88%	3.98%	2050	2700	0.77	0.75	11.90	70	750	500	14.20	0.09	500	690	ND	ND
		1400	ND	2.80%	3.70%	2650	3375	1.00	0.90	12.30	90	2150	950	13.00	0.08	440	620	ND	ND
		1415	ND	1.96%	2.30%	1375	1700	1.10	1.36	13.80	100	2050	1100	9.80	0.16	320	420	ND	ND
		1430	ND	2.41%	3.26%	2850	3575	1.00	2.50	11.90	100	1650	1250	11.80	0.16	375	505	ND	ND
		1445	ND	8600	1.03%	525	750	1.50	2.50	14.20	120	2100	1450	7.20	0.25	155	225	ND	ND
		1460	ND	6600	7800	563	725	2.20	4.75	12.60	130	2550	1500	6.90	0.31	140	195	ND	ND
		1475	ND	525	750	613	625	6.20	5.45	4.70	130	350	1500	7.70	0.82	28	80	ND	ND
	454	1490	ND	1175	1475	325	380	1.80	1.45	3.50	150	350	1100	15.90	0.41	168	255	ND	ND
	466	1531	2.06	1050	1875	41	38	1.50	4.50	14.00	60	1300	900	4.20	0.12	55	110	1.44	1.78
		1551	2.00	1300	2150	15	20	1.35	0.30	16.20	40	1300	450	3.50	0.12	55	110	1.65	1.65
		1571	3.18	1075	1725	11	13	1.50	0.76	16.00	40	3200	1100	4.00	0.11	50	95	0.54	1.60
		1591	2.73	1350	1925	9	13	1.20	0.11	16.00	40	2450	1250	4.10	0.14	58	105	0.79	1.42
		1610	3.01	1000	1675	9	13	1.50	2.77	15.60	70	3200	1250	4.70	0.14	55	105	0.52	1.67
		1630	ND	400	1450	2.5	8	3.10	4.15	12.20	260	2800	2900	4.20	0.17	23	85	0.52	3.62
		1650	3.25	263	1575	6	10	1.80	5.50	15.80	100	3600	1400	4.10	0.08	30	85	0.44	5.99
		1670	1.65	1138	1725	8	10	1.90	5.40	16.00	80	1650	1000	5.00	0.22	60	100	1.04	1.51
		1686	ND	1213	1975	8	10	1.80	1.23	17.20	80	5100	550	5.00	0.14	58	100	1.63	1.62
		1708	2.80	838	1500	21	25	1.80	5.70	15.60	80	2700	1250	4.20	0.17	48	95	0.56	1.79
		1727	3.04	1013	1675	14	20	2.05	2.75	17.20	60	3050	1300	4.50	0.22	53	105	0.56	1.65
	532	1745	ND	6900	8400	136	133	1.80	2.95	13.60	110	2550	950	10.00	0.19	230	405	3.29	1.21

Table 48. Geochemical analyses, canonical scores, Ni/Cr and Ni/NiP ratios for komatiite samples from three core holes at Windarra . Hole C shows analyses above and below a zone of nickel sulphide mineralization. Note that the footwall ultramafic, although high in NiP and CoP, indicating ample sulphur is present, is relatively low in both Ni and Mg compared to the main ultramafic. The relatively high background Ni and NiP in holes B and C relative to the moderate to low Mg content of the komatiites is an unusual feature of both Windarra and Windarra South. The high Cr content of the Windarra komatiites is unique among mineralized ultramafics.

this was a factor, the origin of the nickel is still unresolved. A further possibility is that the sampling was not representative of the komatiite host.

APPENDIX D

ULTRAMAFIC ROCK ANALYSIS BY ATOMIC ABSORPTION SPECTROPHOTOMETRY USING A HYDROFLUORIC/PERCHLORIC ACID DECOMPOSITION TECHNIQUE

D.1 Introduction

Most analyses carried out for this study were completed at Tenneco Australia Inc.'s geochemical laboratory in Melbourne, Australia between 1972 and 1976. The methods and procedures used were devised by W. Guthrie, formerly Chief Chemist for Tenneco Australia Inc. All analyses were carried out under Guthrie's supervision.

The method described herein employs the use of 50% hydrofluoric acid in combination with 70% perchloric acid in teflon vessels, and has been successful in dissolution of almost all ultramafic rock types. Samples which contained substantial chromite were exceptions. These samples normally had a small amount of black residue remaining after the dissolution of the sample. From tests carried out on this residue it was shown that this is chromite which remains unattacked after the acid decomposition of the sample. Since many of these samples have quite a significant chromium value it was evident that the chromium occurred in two forms, namely that part which is attacked by the acid decomposition and is apparently chromium attached to the silicate structure, and secondly, the unattacked chromite. It has also been shown that this chromite molecule has small amounts of Al and Fe in its structure. The ratio of Cr/Al/Fe is not constant in this molecule as can be shown from two examples:

1) R.2147 is an ultramafic rock from the Kambalda area, W.A.

2) UM-4 is an ultramafic rock classified as a "serpentinised hornblende metaperidotite" from the Werner Lake district of north western Ontario (Canadian Mines Department reference sample).

These two samples were digested using the hydrofluoric/perchloric acid technique, the black residues remaining were washed thoroughly and digested using a sodium peroxide fusion technique and these solutions analysed for all elements currently being investigated. The molecular formulae of the black residues were then calculated to be approximately as follows:

Sample R.2147 $3(Cr_2O3.FeO)Al_2O3$.

Sample UM.4 $2\ Cr_2O_3.6FeO.3Al_2O_3$.

Specific sulphide copper, nickel and cobalt analyses were done using the cold leach technique employing ascorbic acid and hydrogen peroxide as described by Lynch (1971). According to Guthrie, the total Cu/NiZn/Mn/Co are true values analytically and are reproducible to better than a 5% relative error. The total Ca/Mg/Al/Ti/Fe/Cr are (within the limits of the technique as described in the earlier part of this discussion, mainly in relation to chromium and aluminum) analytically reproducible to within 10% relative error. The "specific sulphide" analyses for Cu/Ni/Co are purely geochemical methods (i.e. in addition to leaching the sulphides from ores it is highly probable carbonates and some primary oxides are also leached). The analytical reproducibility of the method under carefully controlled laboratory conditions is of the order of 5% relative error.

D.2 Sampling and Preparation

Some samples were received which had already been dried, crushed and pulverised and these were used as received.

A great number of samples, however, were received in chip or rock form and these were crushed to 100% -5 mesh, split to approximately 80 gm size (where necessary) and pulverised. Two methods of pulverisation were used:

1) where small batches were received - samples were pulverised using a "zieb-technique" (chrome steel vessels).

2) Where larger batches were received - samples were pulverised using the Ledir "Multi-mill".

During these operations care was taken to minimise possible contamination from the equipment and absorption of moisture.

D.3 Instruments and Apparatus

All measurements were made with a Varian Techtron model AA-5 atomic absorption spectroph otmeter. An AB-50 high temperature burner was used for acetylene-nitrous oxide flames and an AB-51 burner was used for acetylene-air flames. All determinations were made using Varian single-element hollow cathode lamps. The nebulizer used was a Varian variable (tantalum) one adjusted to an uptake rate of 4.5 ml/min.

It should be noted that the use of other instruments, lamps, burners or nebulizers may necessitate changes in the present methods as to the preparation of sample and standard solutions and standard working conditions.

D.4 Method of Decomposition

1) Accurately weigh 0.2 gm of pulverised sample into a 50 ml "teflon" beaker.

2) Add 2 mls 70% perchloric acid followed by 5 mls 50% hydrofluoric acid and thoroughly wet sample.

3) Place beaker on asbestos covered hot plate (on high setting) and take to slightly moist dry state i.e. until disappearance of dense white fumes; normal digest time - 1½-2½ hours.

4) Remove beaker from hot plate, allow to cool a little, add 2 mls 50:50 hydrochloric acid and replace on hot plate for 15-30 seconds to obtain a clear, sediment-free solution.

5) Make up to 40 mls by the addition of an accurately measured 38 mls of deionized water.

6) Solutions are mixed thoroughly by pouring back and forth once or twice into small plastic containers which have plastic screw caps which are used for storage of sample solutions.

This Is The "Concentrated Sample" Solution:

7) Take a 2 ml aliquot of the concentrate sample (the MLA automatic syringe pipette and plastic disposable pipette tips are ideal for this) and transfer to an erlenmeyer flask containing an accurately dispensed 38 ml of deionised water. Shake to mix solutions thoroughly. Add 5,000 µg ml potassium (approximately 0.4 gm potassium chloride) and shake to dissolve.

This Is The "x 20 Sample Solution" (Dilute Solution):

NOTES:

1) After decomposition, it may be found that traces of "black sediment" are still undissolved in some samples; this material cannot be completely decomposed by

the above decomposition technique and should, therefore, be noted in order that reference can be made to these samples at a later date should this be necessary.

D.5 Standard Solutions

Wherever possible, high grade (merck) metals were used to prepare Standard Solutions; the exceptions to this were: $CaCO_3$ (99% merck) was used for calcium; $K_2Cr_2O_7$(A.R. grade) was used for chromium.

CS-1 STANDARDS A combined 1000 µgn/inl stock solution containing Cu/Ni/Zn/Co

CS-2 STANDARDS A combined 1000 µgn/inl stock solution containing Ca/Mg/Al/Fe

Chromium, manganese and titanium stock solutions were made up separately. In all cases, diluted standard solutions were made up from 1000 µgn/inl stock solutions in the same proportion of acid to that of the unknown samples.

D.6 Reference Samples

1) F. J. Flanigan - Liaison Officer
Analytical Laboratories Branch
United States Department of the Interior
Geological Survey
Washington, D.C. 20242

Standards ref: G-2; GSP-1; AGV-1; PCC-1; DTS-1; BCR-1

2) Canadian Standard Reference Materials Project
C/- Mineral Sciences Division
Mines Branch
Ottawa, Ontario K1A 0G1

Ultramafic Stds. ref: UM-1; UM-2; UM-4

In addition, we managed to secure small portions of rock standards from:

3) La Trobe University, Bindoora, Vic. (ANU 27183; ANU 23182)

4) Victorian Mines Department (USBS 99)

5) Townsor & Mercer (BCS 175/2 - Iron Ore std.)

In all, these reference standards gave a wide choice of chemically and geologically different matrices.

D.7 Copper, Nickel, Zinc, Cobalt, Chromium, Manganese - Standard Conditions

Standard conditions for the above are as per Varian publication entitled "Analytical Methods for Flame Spectroscopy".

Flame Stoichiometry is particularly important with:

1) Manganese - a highly oxidising (very lean) C_2H_2/air flame is necessary to overcome matrix interferences (otherwise N_2O/C_2H_2 flame).

2) Chromium - optimum flame stoichiometry slightly oxidising is very important in air/CaH_2 flame to overcome matrix interference (otherwise the use of an N_2O/C_2H_3 flame is recommended).

3) Nickel - oxidising air/C_2H_2flame (otherwise N_2O/C_2H_2). Check for non-atomic absorption by the use of the H_2 continuum lamp.

Burner heights and angles are adjusted to allow differing concentrations to fall within a set standard series.

D.8 Calcium: Standard Conditions

For Concentrated Samples and x 20 Dilutions

Special synthetic standards used (hereafter called CS-2 standards). However, please note remarks at foot of page.

D.8.1 Conditions

N_2O/C_2H_2 reducing flame (sl. fuel rich); slit width = 100 μ; 10 mA; 4228A°, burner at ht. = 6.5 at approx. 30° angle (using 50 PPM CS-2)

D.8.2 Comments

Because of the wide variance in calcium levels in samples it is quite often necessary to use two different scales.

1) 5,10,20,50 PPM CS-2 standards: cover range 0.1-1.0% (conc.)
and 2.0-20% (dil.)

Adjust burner angle to give 50 PPM 70 aos. units.

2) 1,5,10 PPM standards: cover range <0.01-0.2% (conc.)
and 0.4-4.0% (dil.)

Burner approximately longwise to give 10 PPM 65-70 abs. units.

D.8.3 Other Remarks

1) Calcium analysis is plagued by interferences particularly in complicated matrices; these are apparently overcome by the use of the N_2O/C_2H_2 flame, however, ionisation of the calcium itself (80-90%) occurs in this flame and it is therefore necessary to add a more readily ionisable salt such as potassium (5000 μg/ml) to both standards and unknowns (conc. and diluted solutions) to overcome this interferent.

2) At the calcium levels where it is possible to calculate percentage calcium using either concentrated or diluted solutions, some error is apparent between the two results - this however could be due to the inaccuracies of the graph work at these particular levels or indeed high matrix level interferences (conc. samples).

Ideally, all calcium should be analyzed by A.A. using the diluted samples, however, this could involve time-consuming graph work (3 or possibly 4 different graphs). However, if this were done and also special working standards used for graph calibration, better results and reproducibility would undoubtedly result.

D.9 Aluminum: Standard Conditions

For Concentrated Samples and x 20 Dilutions

Special synthetic standards used (hereafter called CS-2 standards). However, please note remarks at foot of page.

D.9.1 AA. Conditions

N_2O/C_2H_2 reducing flame (fuel rich); slit width = 50 μ; 10mA; 3093A°, burner ht. ≙ 7.5; use of expanded scale necessary.

D.9.2 Comments

Use 4,10,20,50 PPM CS-2 standards which cover range:

concentrated samples - 0.01 - 1.0%

diluted samples - 1.0 -20%

Conditions should be set up using 50 PPM standard ≙ 70-75 abs. units by adjusting C_2H_2 flow to give maximum sensitivity and then using scale expansion to obtain desired reading. Initially, say first 20 samples, it may be necessary to adjust C_2H_2 flow a little, thereafter it is only necessary to adjust scale expansion to maintain steady and constant meter readings.

D.9.3 Other Remarks

1) Use of the CS-2 Synthetic Standards is made for one very important reason: namely, the possibility of incomplete digestion of the total amount of aluminum present in the sample. (This is normally a very small quantity and is the aluminum tied up in the undigested Chromite molecule - refer to the main body of this report for further details.)

However, good agreement between outside laboratories and ourselves has been obtained using the synthetic standards.

2) Ideally, all analyses should be done on the diluted sample, although this is particularly impractical with samples with an extremely low aluminum content (<0.5%).

3) Varian report that aluminum is partially ionised in the N_2O/C_2H_2 flame - this is overcome by the addition of 2000 µg/ml K+ (as chloride) which suppresses the ionisation thus overcoming the enhancement effect from other alkali metals.

D.10 Iron: Standard Conditions

For x 20 Dilutions

Special Working Standards Used (in diluted form)

1) USBS.99: ANU.27183 (50:50) = 1.71% Fe

2) ANU.27183 = 3.37

3) USBS.99: ANU.23182 (50:50) = 4.71

4) ANU.23182: ANU.27183 (50:50) = 6.37

5) ANU.23182 = 9.36

6) 15642 = 13.50 *

* has not been exactly established

For High Fe Values

7) 175/2 BCS: USBS.99 (50:50) = 33.08% Fe

8) 175/2: ANU.23182 (50:50) = 37.73

9) 175/2 = 66.10

D.10.1 AA Conditions

air/C_2H_2 flame air=6¼/15 PSI C_2H_2=2¼ (i.e. oxidising to stoichiometric)

5mA; burner ht=10 @ approximately 15° angle to horizontal

slit width = 50 μ; 2483A°.

D.10.2 Comments

Conditions should be set up using high (e.g. 15642) working standard. Absorbance signal normally remains steady, however, occasional checks are warranted on C_2H_2/air conditions and adjusted accordingly and any slight absorbance difference adjusted by altering burner angle.

c/s 15642 should $\triangleq$ 54 abs. units.

D.10.3 Other Remarks

Chemical (and possibly physical) conditions give rise to interference problems which have not as yet been fully investigated, hence the reason for using the above working standard solutions instead of the synthetic CS-2 standards.

In the future it may be easier to use some other working standards instead of some of the 50:50 mixed ones above, as we now have more check samples readily available.

D.11 Magnesium: Standard Conditions

For x 20 Dilutions

Special Working Standards Used (in diluted form)

1) ANU.27183 = 1.14% Mg
2) 15542 = 4.30
3) ANU.23182 = 6.43
4) 15642 = 10.00
5) 15641 = 15.60
6) 15506 = 19.50
7) 15628 = 24.84

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8) PCC-1 = 26.20
9) DTS-1 = 30.00

D.11.1 AA. Conditions

N_2O/C_2H_2 (stoichiometric or slight oxidising) flame; 5mA; 2852A^o; burner @ right angles and height $\triangleq$ 3.0. slit width = 100 μ.

D.11.2 Comments

Conditions should be set up using high (e.g. 15506) working standard. Absorbance signal increases continually and therefore a steady absorbance reading should be maintained by alteration of burner height at regular time intervals.

c/s 15506 should be $\triangleq$ 50 abs. units.

D.11.3 Other Remarks

CS-2 standards give much higher (20-50%) results and therefore some form of chemical and/or physical interferences are apparent. This has not been fully investigated yet hence the reason for using special working standards for graph calibration.

(There are no reported interferences on magnesium determination using an N_2O/C_2H_2 flame according to LANGMYHR AND PAUS, however Varian literature report a

general absorbance enhancement of 15% by the alkali metals in an N_2O/C_2H_2 flame due to suppression of ionisation.)

D.12 Titanium (as Titanium Dioxide):

For Concentrated Samples

Special Working Standards Used (in concentrated form)

1) PCC-1 = 0.02% TiO_2

2) G-2 = 0.53% TiO_2

3) GSP-1 = 0.69% TiO_2

4) AGV-1 = 1.08% TiO_2

5) BCR-1 = 2.23% TiO_2

Additional Check Samples

6) ANU.27183 = 0.57% TiO_2

7) ANU.23182 = 1.93% TiO_2

D.12.1 AA. Conditions

N_2O/C_2H_2 highly reducing flame (fuel very rich); slit width = 50 μ; 20mA; 3643A°; burner ht. ≙ 8; use of expanded scale necessary.

D.12.2 Comments

Conditions should be set up using high standard e.g. BCR-1 or ANU.27183 ≙ 70 abs. units by adjusting C_2H_2 flow to give maximum sensitivity (very fuel rich) and then using scale expansion to obtain desired reading. Initially, say first 20/30 samples, it will be necessary to adjust C H flow a little to maintain constant readings; thereafter it is only necessary to adjust scale expansion to maintain steady and constant meter readings.

D.12.3 Other Remarks

Interferences are numberous and various releasing agents are recommended (refer Varian literature on standard conditions, also LANGMYHR AND PAUS).

However, use of the above working standards and methodology has given good reproducibility and, from work done to date, shows good agreement with outside sources.

APPENDIX E

MULVAR - DISCRIMINANT ANALYSIS

MULVAR is a multivariate analysis "programme" for canonical analysis and principal components analysis. It is designed to provide an analysis of multivariate data involving variation between and within groups, particularly an analysis of the variation within groups (principal components analysis), as well as the variation between groups relative to that within groups (canonical analysis).

Program options include:

1) principal components analysis of the covariance matrix or the correlation matrix or both for each group;

2) multivariate test of the homogeneity of the covariance and correlation matrices (Bartlett's test) - this requires the calculation of the determinant of each matrix if a principal components analysis is not carried out;

3) principal components analysis of the pooled within-groups covariance and correlation matrices;

4) principal components analysis of the between-groups matrix;

5) canonical analysis, based on the unweighted between-groups matrix, i.e., the variation of the group means about their overall mean, ignoring the number of observations within each group (not usually specified);

6) canonical analysis based on the usual between-and within-groups matrices, i.e., $(\underset{\sim}{B} - \mu\underset{\sim}{W})\underset{\sim}{c} = \underset{\sim}{0}$ where $\underset{\sim}{T} = \underset{\sim}{B} + \underset{\sim}{W}$

Because of the possibility of unequal covariance matrices, an option is available to ignore the covariance (or correlation) matrix for a particular group(s). Thus the between-groups matrix is calculated from the variation of the group means about their overall mean, weighted for the number of observations within each group.

7) canonical variate scores for each group, and the mean and variance for each canonical variate for each group. The latter provides a useful check on the effect of lack of homogeneity of variance within groups, since the pooled variance for each

canonical variate equals unit; the variance for each group should also be close to one.

8) a plot of the transformed group means for the first three canonical variates, i.e., CVI vs. CVII, CVI vs. CVIII and CVII vs. CVIII.

9) Mahalanobis' D^2 for each pair of groups.

Two options are available:

i) D^2 calculated from the pooled within-groups matrix - the usual method of calculation;

ii) D^2 calculated for each pair of groups, from the pooled covariance matrix for that pair of groups.

10) Gower's (1966) principal co-ordinates analysis of the matrix of D^2 values, with graphical oupput of the results. (A principal co-ordinates analysis is effectively a principal components analysis of the "similarity matrix", with the rows and columns adjusted to sum to zero, and the eigen-vector scaled so that the sum of squares equals the corresponding eigen-value.)

The rationale behind (9) and (10) follows from Gower's result that a principal co-ordinates analysis of the matrix of D^2 values gives the same representation of group separation, in the reduced number of dimensions considered, as a canonical analysis.

Thus a principal co-ordinates analysis of the two alternative D^2 matrices should give an indication of the effect of the heterogeneity of the group covariance matrices on the resulting group differences.

Computational Procedures

The eigen-values and vectors are calculated using a standard computing centre library package, using the Jacobi method.

Only the upper diagonal of a square symmetric matrix is stored. Arrays are used, rather than matrices.

Because of its extreme flexibility in statistical work the Cholesky decomposition (square root method) to triangular form is used to calculate the determinants of the covariance (and hence correlation matrices) for Bartlett's test, when a principal components analysis is not specified. This subroutine is also used for the canonical analyses.

To calculate the canonical roots and vectors, the within-groups matrix is decomposed to the triangular form. Pre- and post-multiplying the between-groups matrix by the inverse of the triangular matrix (see below) gives a square symmetric matrix. The eigen-values of this matrix give the canonical roots while the eigen-vectors, pre-multiplied by the triangular matrix, give the canonical vectors, i.e.,

for $(\underset{\sim}{B} - \mu\underset{\sim}{W})\underset{\sim}{c} = \underset{\sim}{0}$

or $(\underset{\sim}{W}^{-1}\underset{\sim}{B} - \mu\underset{\sim}{I})\underset{\sim}{c} = \underset{\sim}{0}$

let $\underset{\sim}{W} = \underset{\sim}{U}'\underset{\sim}{U}$

where $\underset{\sim}{U}$ is upper triangular.

Now the matrix $\underset{\sim}{U}'^{-1}\underset{\sim}{B}\,\underset{\sim}{U}^{-1}$ is square symmetric.

Consider $(\underset{\sim}{U}'^{-1}\underset{\sim}{B}\,\underset{\sim}{U}^{-1} - \lambda\underset{\sim}{I})\,\underset{\sim}{x} = \underset{\sim}{0}$

i.e., $\underset{\sim}{U}'^{-1}\underset{\sim}{B}\,\underset{\sim}{U}^{-1}\,\underset{\sim}{x} = \lambda\underset{\sim}{x}$.

Pre-multiplying by $\underset{\sim}{U}^{-1}$ gives $(\underset{\sim}{U}^{-1}\,\underset{\sim}{U}'^{-1})\,\underset{\sim}{B}\,\underset{\sim}{U}^{-1}\,\underset{\sim}{x} = \lambda\underset{\sim}{U}^{-1}\,x$

i.e., $\underset{\sim}{W}^{-1}\,\underset{\sim}{B}\,\underset{\sim}{U}^{-1}\,\underset{\sim}{x} = \lambda\underset{\sim}{U}^{-1}\,\underset{\sim}{x}$

i.e., $(\underset{\sim}{W}^{-1}\,\underset{\sim}{B}\,\lambda\underset{\sim}{I})\,\underset{\sim}{U}^{-1}\,\underset{\sim}{x} = \underset{\sim}{0}$

$\Rightarrow$ $\mu = \lambda$

and $\underset{\sim}{c} = \underset{\sim}{U}^{-1}\,\underset{\sim}{x}$

Thus μ and $\underset{\sim}{c}$ give the required solution.

In the running of the programme, the form of the analysis is controlled by a parameter card specifying the complete analysis, and a parameter card for each group, which specifies the principal components analysis required for each group.

The data may be read directly from cards, or from disc or tape file. The latter is facilitated by coding the first five (alphanumeric - ascii) characters of the data file for each group as a "file name".